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Naval Surface Warfare Center
Philadelphia, PA 19112-1403

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Technical Report

Assessment of Advanced Logistics Delivery System (ALDS) Launch Systems Concepts

by

Gregory W. Anderson, Joseph P. Borraccini,
Brian K. Fitzpatrick, William A. Lynch, Patrick J. McGinnis,
Mark J. Roberts, Michael E. Slipper

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14. ABSTRACT
The Advanced Logistics Delivery System (ALDS) concept proposes the use of ship launched, unmanned gliders to re-supply shore based ground forces and requires a launch system capable of delivering unpowered UAVs to a range of 50 miles. A study to analyze the machinery technologies capable of meeting this requirement dentified a near term solution based on electric linear motor technology derived from the Electromagnetic Aircraft Launch System (EMALS) and incorporating superconductive materials in the rotor, stator windings, and electrical wiring. The development of structurally robust, high capability cryo-cooling components was identified as the most critical effort required to field a prototype system in the 10 to 15 year timeframe. The far term solution proposed was based on advances in rail gun technology anticipated as a result of Navy rail gun technology development projects currently planned for the next decade.

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Contents

Figures

Page

Tables

Page

Administrative Information

The work described in this trade study and technical assessment documents a two-month effort to identify and evaluate candidate machinery concepts for a Linear Electric Launch Actuator System capable of supporting the preliminary Advanced Logistics Delivery System (ALDS) launch system requirements. This work was performed by a multi-disciplinary team of Navy technical experts from the Machinery Science and Technology Branch (Code 984) at the Philadelphia Site of the Naval Surface Warfare Center, Carderock Division (NSWCCD),

Acknowledgements

The team would like to thank Kelly Cooper, Dr. Colen Kennell, and Geoff Hope for the opportunity to assist in the concept development of the ALDS Launcher System. This collaborative effort has received generous technical and scientific support from many individuals. In this regard, the authors are particularly grateful for the contributions of NSWCCD colleagues Sam Doughty, Tom Fikse, Steve Kolesar, Thong Ly, and Neal Sondergaard.

Executive Summary

The Advanced Logistics Delivery System (ALDS) concept developed by the Center for Innovation in Ship Design (CISD), proposes the use of ship launched, unmanned gliders to re-supply shore based ground forces and requires a launch system capable of delivering unpowered UAVs to a range of 50 miles. The Machinery Science and Technology Branch of the Naval Surface Warfare Center's Carderock Division performed this study to analyze the machinery technologies capable of meeting this requirement and developed two solutions based on a program of near term and far term technology development.

The near term solution proposes electric linear motor technology derived from the Electromagnetic Aircraft Launch System (EMALS) currently under development for deployment on the next generation of Navy aircraft carriers. The extension of this technology to ALDS is based on a permanent magnet linear motor design incorporating high temperature superconducting materials in the rotor, stator windings, and electrical wiring. The development of structurally robust, high capability cryo-cooling components was identified as the most critical effort required to field a prototype system in the 10 to 15 year timeframe.

The far term solution was proposed to capitalize on the advances in rail gun technology anticipated as a result of the Navy's rail gun technology development projects currently planned for the next decade. Application of this technology would require scaling rail gun concepts to the ALDS launch speed and vehicle weight requirements in order to demonstrate a prototype in the 2020 timeframe. The development of a suitable electrical interface and curved track structure capable of handling the high current and mechanical loads imposed by a rail gun in this configuration was identified as the most critical effort required to field a prototype system in the 15 to 25 year timeframe.

Existing technical capabilities in the areas of energy storage and power electronics were also examined to identify suitable candidates for the major sub systems needed to support the two solutions. While present energy storage technologies were judged adequate for the solutions proposed, the total size and weight of the system would benefit from additional development. A proposed system derived from EMALS was identified as the most capable power electronics solution since commercial units were deemed inadequate at the power levels required. Additional research to develop more capable switching devices and control algorithms was identified as a pre-requisite to achieving the high power and high frequencies needed for the proposed linear motor.

ROM estimates of the weight and volume characteristics for each solution were determined as shown below. Volumes are for components only and do not include requirements for access.

Table 1 – ALDS Launch System ROM Weight and Volume Summary

System Configuration	Actuator		Electronics		Storage		Total	
	Weight	Volume	Weight	Volume	Weight	Volume	Weight	Volume
Linear Motor	~30	~20	~26-35	~83-146	~20-30	~30	~76-95	~133-196
Railgun	~5	~5	~26-35	~83-146	~20-30	~30	~51-70	~118-181
Weight (metric tons); Volume (cubic meters)								

Objective

The objective of this effort is to identify and evaluate candidate machinery concepts for a Linear Electric Launch Actuator System capable of supporting the preliminary requirements of the Advanced Logistics Delivery System (ALDS) launch system [1].

Background Information

The Advanced Logistics Delivery System (ALDS) is an advanced sea-based concept capable of providing rapid sustainment of goods and supply to expeditionary naval forces. The system consists of a shipboard catapult launcher, notionally shown as a red line on the deck of the launch vehicle in Figure 1, and an autonomous, unmanned glider composed of a central launch body with inflatable wings as shown as the "flying wing" in upper left corner of Figure 1 – Advanced Logistics Delivery System Concept. The centerbody of the flying wing is designed to house enclosed payload, necessary avionics, and inflatable wings. The glider remains in the centerbody configuration with wings stored during the high-speed acceleration launch and climb-out to minimize drag and energy loss. During its steep ascent, the kinetic energy provided to the glider by the launcher is converted into potential energy until the glider reaches its maximum altitude. The vehicle then glides at relatively slow speed to the delivery point.

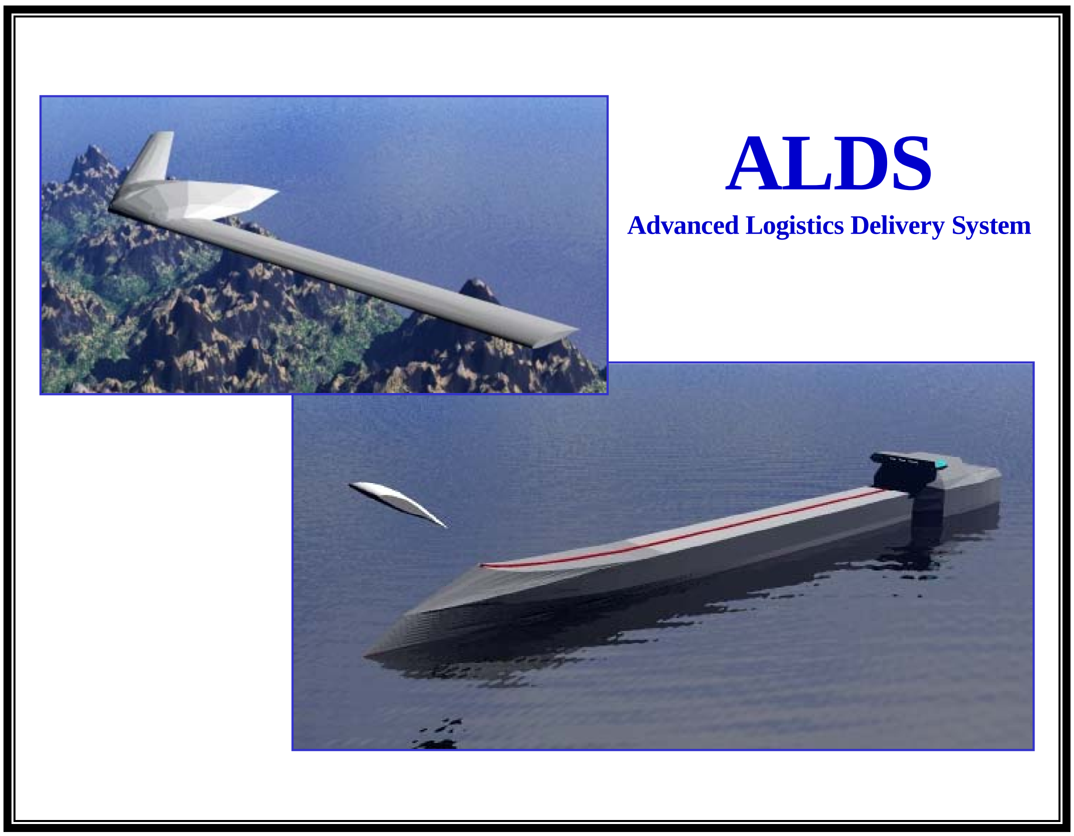


Figure 1 – Advanced Logistics Delivery System Concept

For this investigation, efforts focused on the ALDS launcher system and applicable technological advances in launcher technology. One of the current ALDS launcher system considerations is the linear induction motor concept similar to the Electro-Magnetic Aircraft Launcher System (EMALS) that is currently under development for use as a catapult on a future aircraft carrier. Although the concept is similar, the requirements for ALDS differs significantly from EMALS in launch vehicle mass, launch speed, and required acceleration.

A set of notional design requirements adopted during earlier ALDS design studies will be used to baseline our trade space and technical assessment. Key parameters provided include (a) launch body specifications such as wing span, root chord, empty weight, and payload; (b) launch requirements including launch speed, launch rate, and range; and (c) baseline track configuration data, e.g. track length, launch tube diameter, and launch angle. For continuity, Reference [3] provides an overview of the initial ALDS concept design effort including development of the set of notional requirements used in this investigation.

Project Scope

Approach

Due to the limited project duration (2-month time period), a concurrent engineering approach was used to analyze and develop, in parallel, each of the basic configuration elements or subsystems within the overall launcher system. For this development effort, the conceptual ALDS Launch System is comprised of a Launch Actuator and associated structures, Electric Power distribution, conversion, storage, and control, and Thermal Management subsystems. The inter-relationships of the major subsystems are depicted in Figure 2 – Basic Configuration Elements.

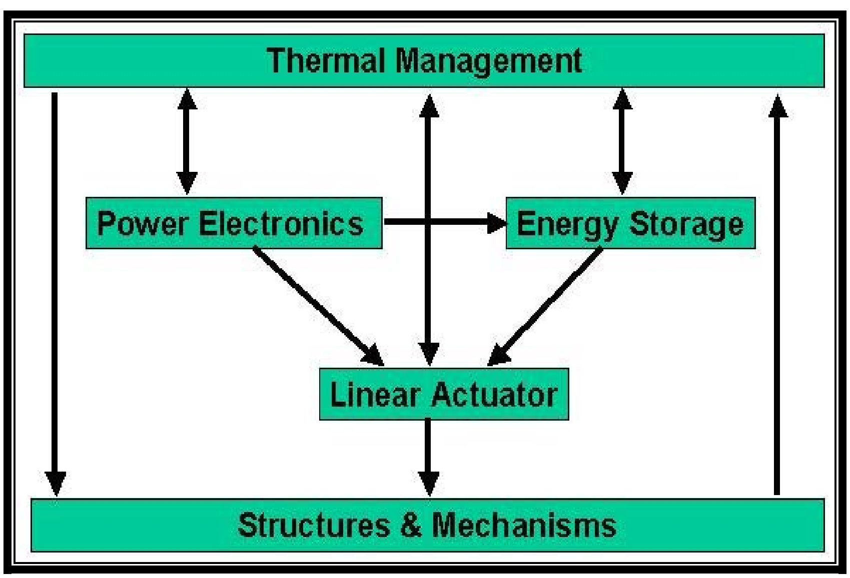


Figure 2 – Basic Configuration Elements

Project Sub-Task Breakdown

The process used to identify and assess various system concepts was broken down into the following project tasks:

Subsystem Concept Trade Study

This task identified and assessed the various system concepts available to implement the desired functionality. Potential system concepts considered included: a linear induction motor (LIM) concept similar to that currently under development for use as a catapult on aircraft carriers, magnetic levitation, and rail gun technology.

Subsystem Technology Assessment

This task identified, assessed and examined current and developmental technologies available to support the required major machinery subsystems and component functionality. Potential technologies included: induction and permanent magnet linear motors; high temperature superconductive materials; hybrid power electronics and power conversion topologies.

System Concept Options

This task integrated the subsystem concept trade study with the subsystem technology assessment to produce a matrix of potential system concept options.

System Capacity & Sizing

This task developed preliminary estimates of the volume, weight and cost for each system concept option.

Notional ALDS Launcher System Design Requirements

In order to identify and evaluate candidate machinery concepts for a Linear Electric Launch Actuator System capable of supporting ALDS requirements, key launcher system operational requirements and design parameters were provided. This preliminary information, summarized in Table 2 – Notional ALDS Launcher System Design Criteria, was used to bound our trade space and technical assessment. The list includes launch body, i.e. launch vehicle specifications, launch requirements, and baseline track configuration data.

Table 2 – Notional ALDS Launcher System Design Criteria

Launch Body Specifications
• Span = 9.8 ft (3m)
• Root Chord = 14.8 ft (4.5m)
• Gross Takeoff Weight = 1500 lbs (681kg)
• Empty Weight = 227 kg (500 lbs)
• Payload = 454 kg (1000 lbs)
Launch Requirements
• Launch rate: Every 2 minutes
• Launch speed = 257 m/sec (500 knots)
• Required acceleration = 30g – 45g
Baseline Track Configuration Data
Track length = 365 ft (~111 meters)
• Launch Angle = 30º (degrees)
• Launch Tube = 10 ft dia.

Track Configuration Requirements

An overview of the layout of the launch tube that encloses the track and its integration with the conceptual ALDS ship is illustrated in the three-dimensional arrangement depicted in Figure 3 – ALDS Launch Trimaran 3D Model. In previous ALDS studies [1,3], multiple designs for a linear motor launch track configuration were evaluated and it was determined for the ALDS application, a baseline track design would be one with a curved section with the largest radius of curvature allowable within the ship deck height that yields a launch angle of 30 degrees. This results in a 183 ft length for the horizontal portion of the track and a 182 ft arc length for the section leaving with 10 ft of the track being above deck. The track configuration is depicted in the conceptual ship profile (Figure 4 – Conceptual Profile View of ALDS Launch Trimaran) and the baseline dimensions are shown in Figure 5 – Baseline Track Configuration Requirements.

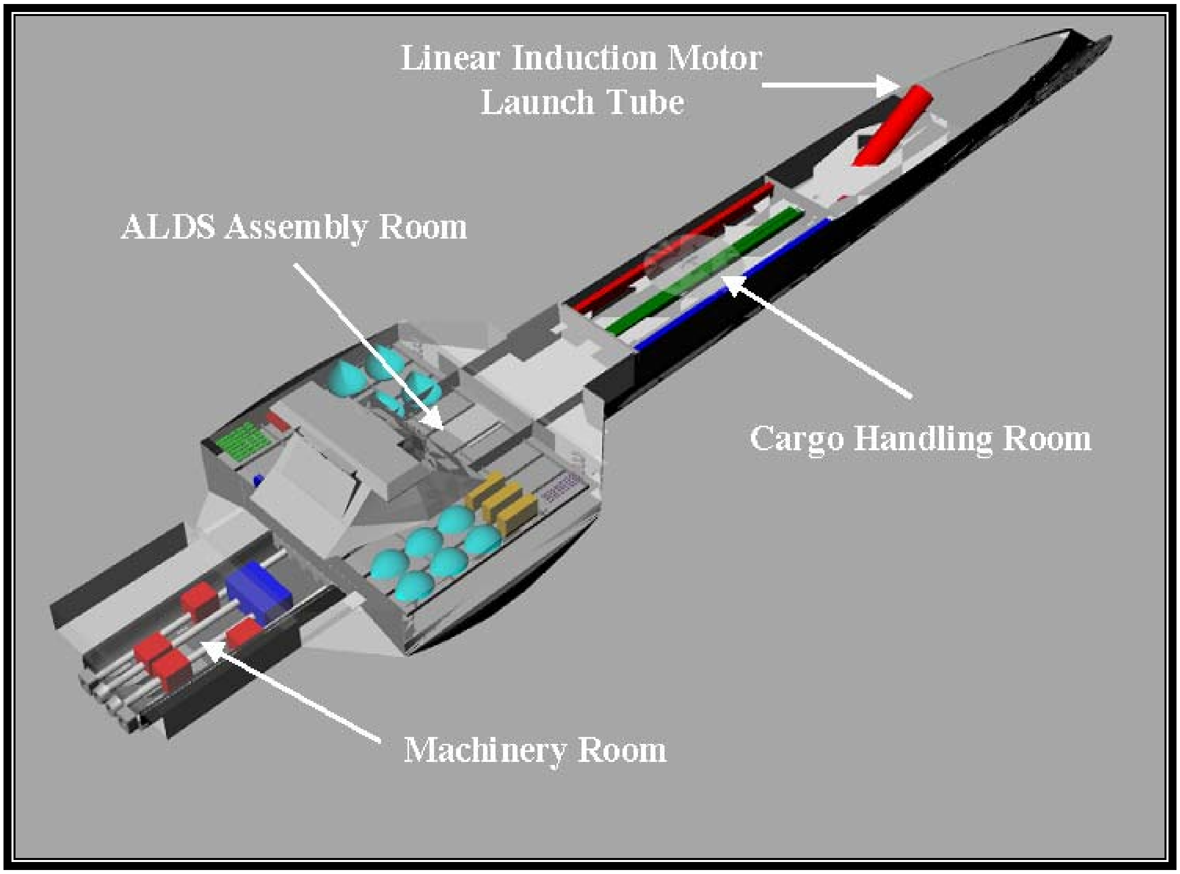


Figure 3 – ALDS Launch Trimaran 3D Model

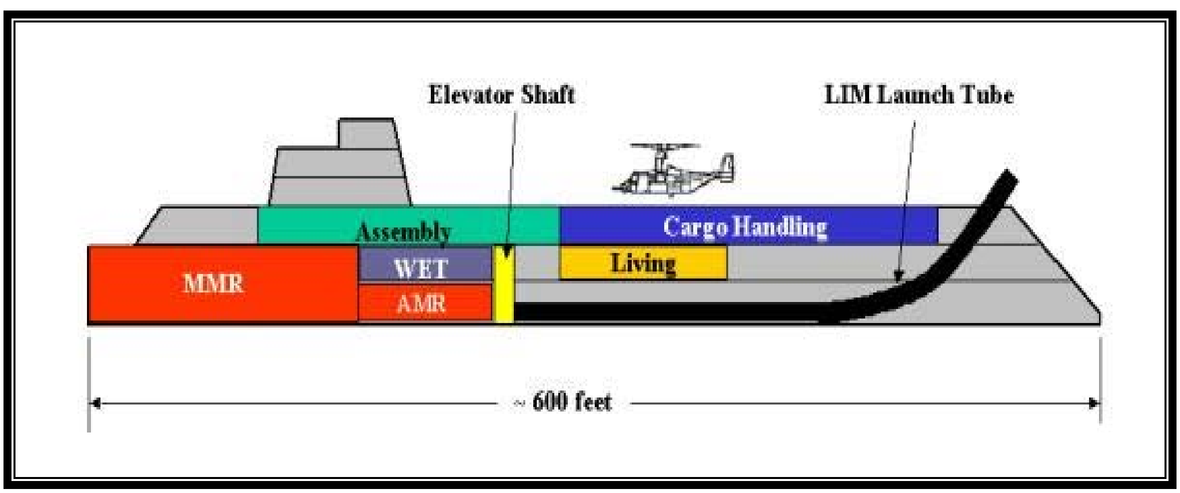


Figure 4 – Conceptual Profile View of ALDS Launch Trimaran

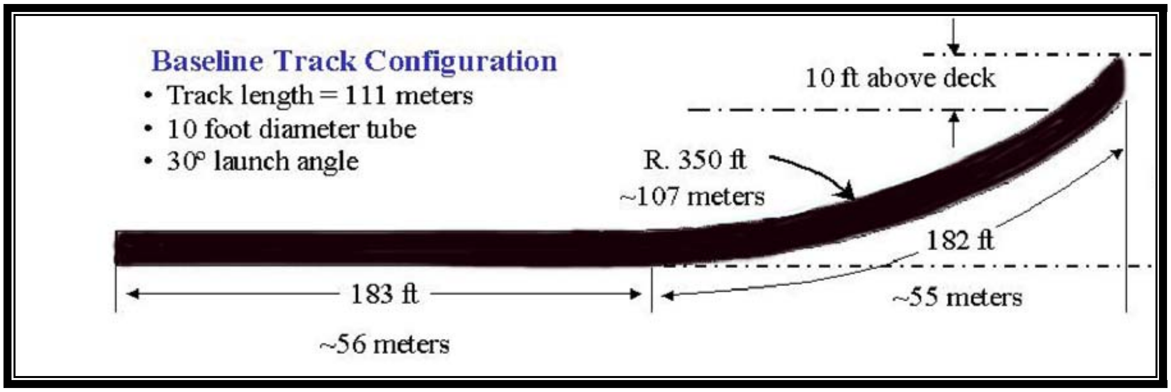


Figure 5 – Baseline Track Configuration Requirements

Once the launcher system parameters provided were evaluated and the major system elements and technology options were identified, the following methodology was developed.

- Determine Shuttle Launch/Retrieval Configuration
- Establish baseline track configuration
- Establish baseline power requirements
- Identify system concept options
- Evaluate candidate technologies
- Identify relevant characteristics/pros & cons
- Establish ROM sub system/component requirements
- Establish ROM Weight & Volume
- Identify near term & far term configurations & future studies

Launch Configuration and Power Requirements

The parameters impacting the launch process were identified and evaluated against the possible shuttle launch and retrieval configurations. An ALDS Launch Analysis Tree, shown in Figure 6 , was used to graphically highlight the key parameters for this assessment.

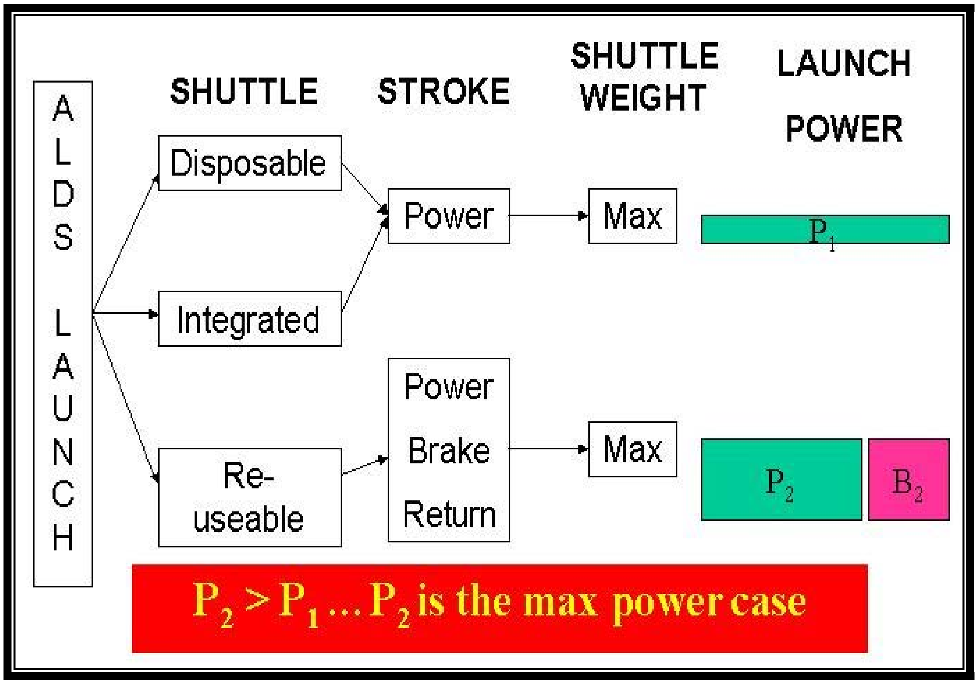


Figure 6 – ALDS Launch Analysis Tree

In the preliminary analysis, the worst-case shuttle launch configuration with respect to power requirements involved the case of a reusable shuttle due to the requirement of the additional brake-stroke and return-stoke i.e. launch and retrieval. Preliminary motor force requirements were then determined assuming a shuttle mass ranging between 100-200 kg and track launch and braking lengths of 345 ft and 20 ft, respectively. The resultant motor force requirements are depicted in Figure 7 - Shuttle Mass versus Required Motor Force. The black line indicates the force required to achieve launch velocity in 345 ft for various shuttle masses and the red line indicates the force required to brake the shuttle in the allotted 20 ft. Since the shuttle mass is a fraction of the total launch package mass being accelerated, the black line is fairly horizontal. The red line is considerably steeper since the shuttle mass is the only mass being decelerated. Results from this initial analysis drove us to investigate in much more detail the relative effects of launch length and shuttle mass. The peak power requirements for a disposable shuttle (lower blue line) and re-usable shuttle (upper violet line) at the extremes of this weight range are shown in Figure 8 –Shuttle Mass vs Peak Power.

For the case of a launch and retrieval system with a reusable shuttle, adjustments need to be made to the acceleration and deceleration lengths of the overall track to account for the additional brake-stroke and return-stoke. Table 3 - Shuttle Acceleration / Deceleration Lengths shows the effect of shuttle mass on the track configuration when launch power is assumed equal to brake power. For a re-usable 200 kg shuttle case, the length of track available for shuttle (and glider) launch is reduced to 91 meters and the remaining 20 meters is available for the braking phase.

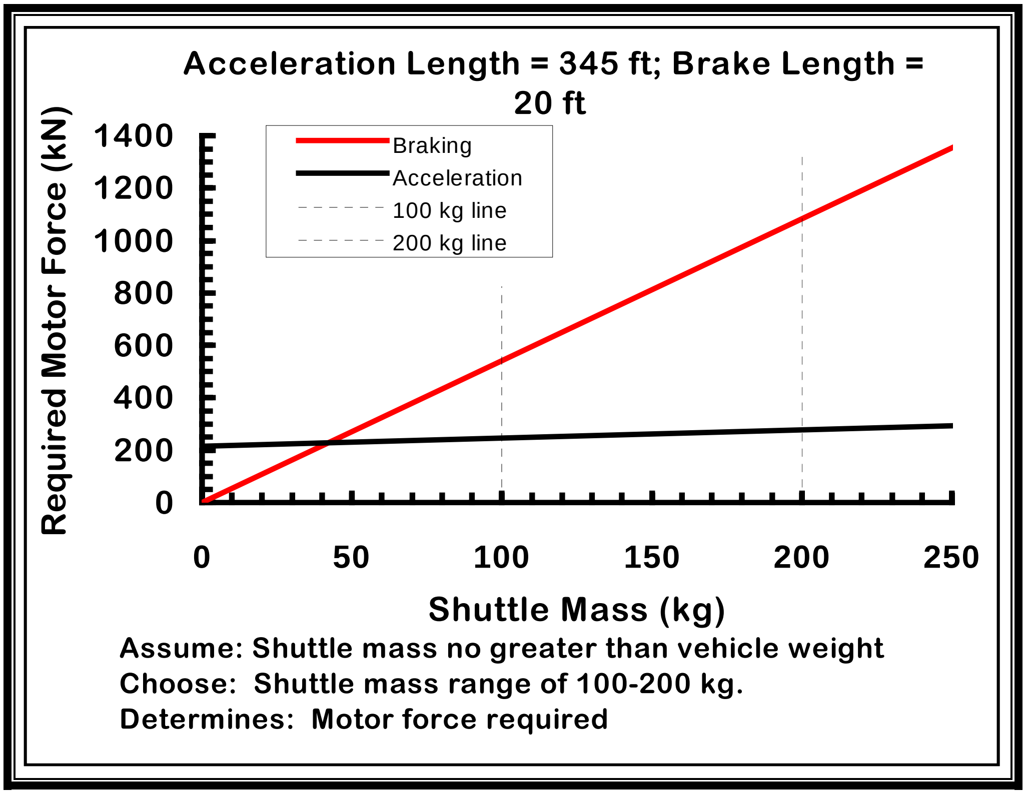


Figure 7 – Shuttle Mass versus Required Motor Force

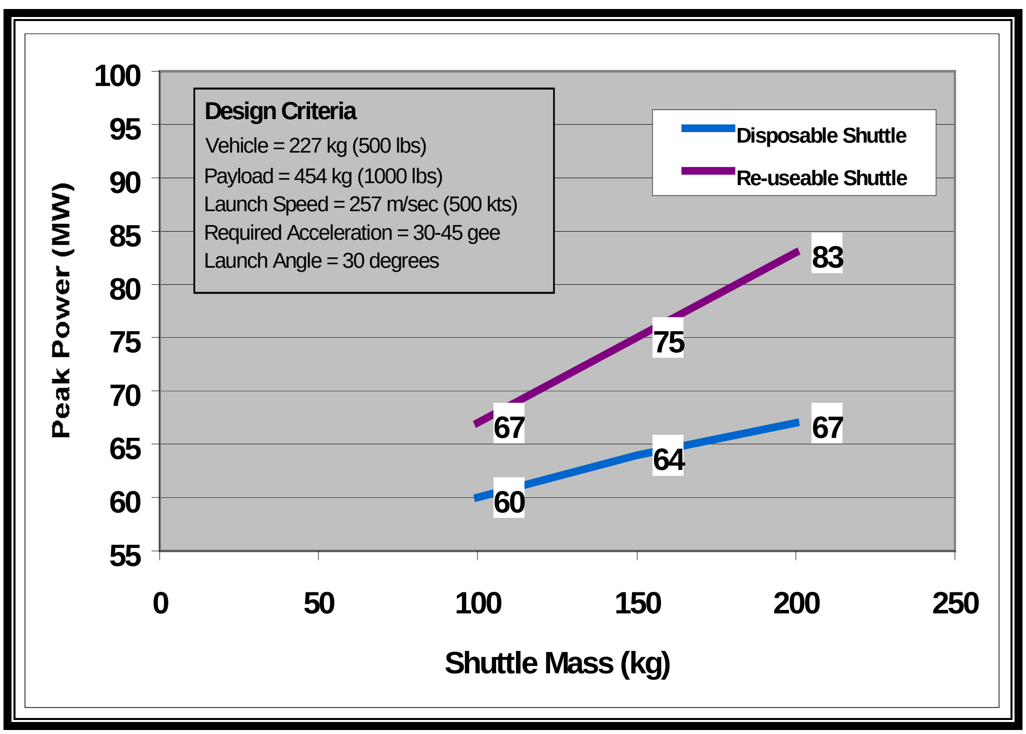
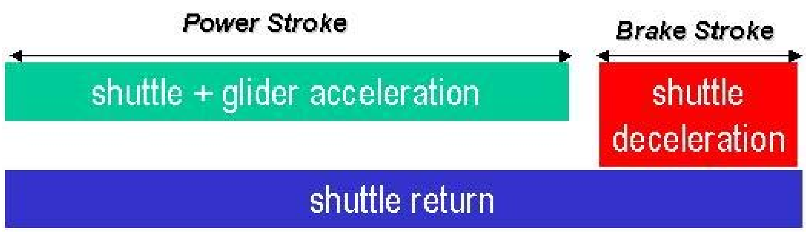


Figure 8 – Shuttle Mass versus Peak Power

Table 3 – Shuttle Acceleration / Deceleration Lengths



Assume launch power = brake power

SHUTTLE WEIGHT kg	POWER – BRAKE STROKE meters
200 (Disposable)	111 – 0
100 (Re-usable)	98 - 13
200 (Re-usable)	91 - 20

System Concept Trade Studies

Linear Actuator Options

One of the major components evaluated in the preliminary ALDS concept was the use of a linear motor launching system similar to the EMALS system currently under development for use in the catapult design on aircraft carriers. In the EMALS system, a linear induction motor (LIM) was the motor of choice in the launcher design. For the ALDS application, a decision needs to be made as to the choice of linear motor for the final launcher design. The linear actuator motor topologies considered for the ALDS Launcher system are shown schematically in Figure 9 – Linear Actuator Motor Topologies and in a matrix format in Table 4 – Motor System Characteristics. A qualitative analysis was conducted to evaluate each of the motor types against ten functional areas or weighting parameters: Gravimetric Power Density, Volumetric Power Density, Cost, Efficiency, Power Factor, Complexity, Current Collector issues, Power Electronic issues, Acoustic Signature, and Technology Readiness Level (TRL). Motor topologies with less favorable weighting parameters (depicted as having many “red” or “yellow” squares) were ruled out for further investigation. Results of this analysis are presented in the lower Table 4.

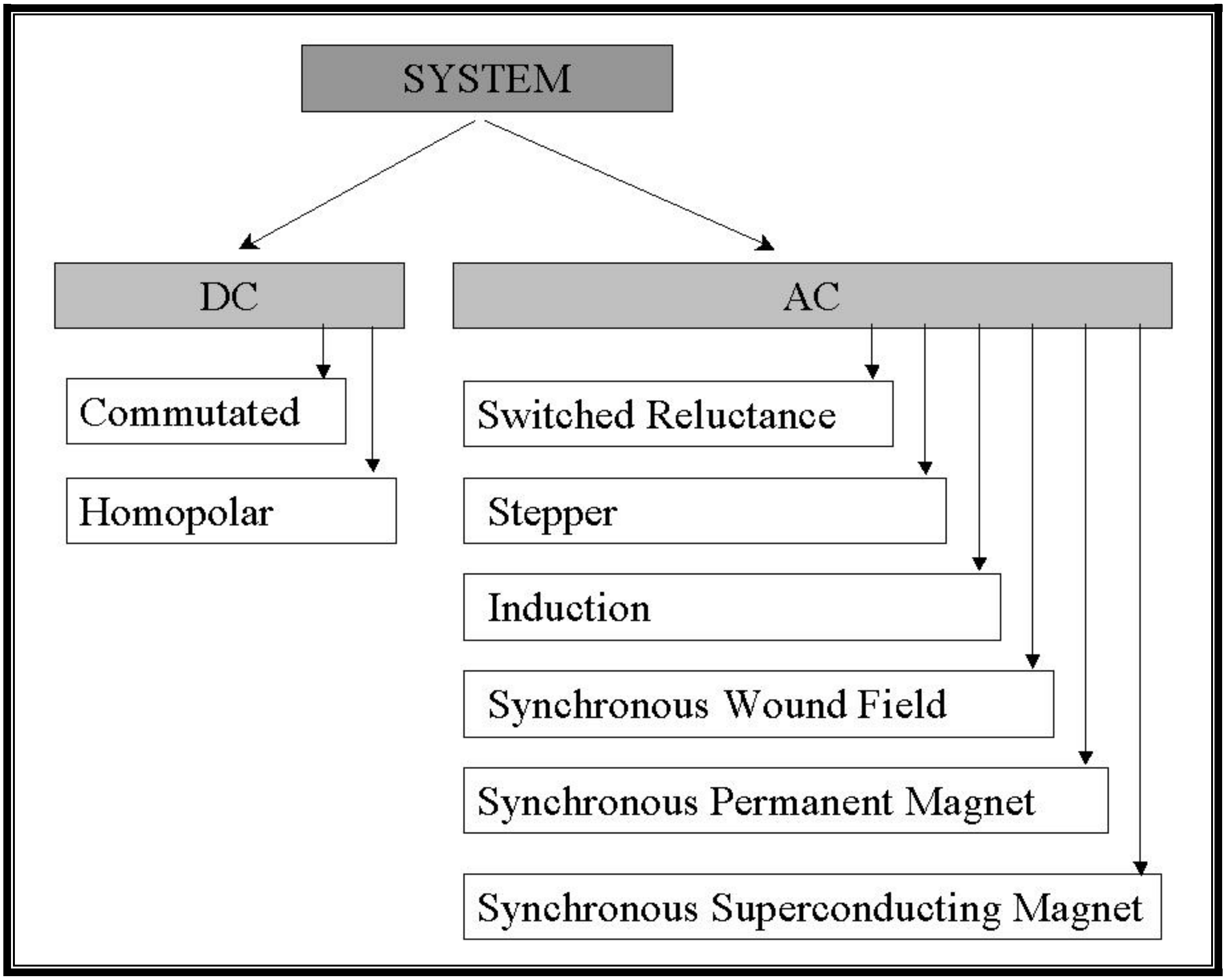
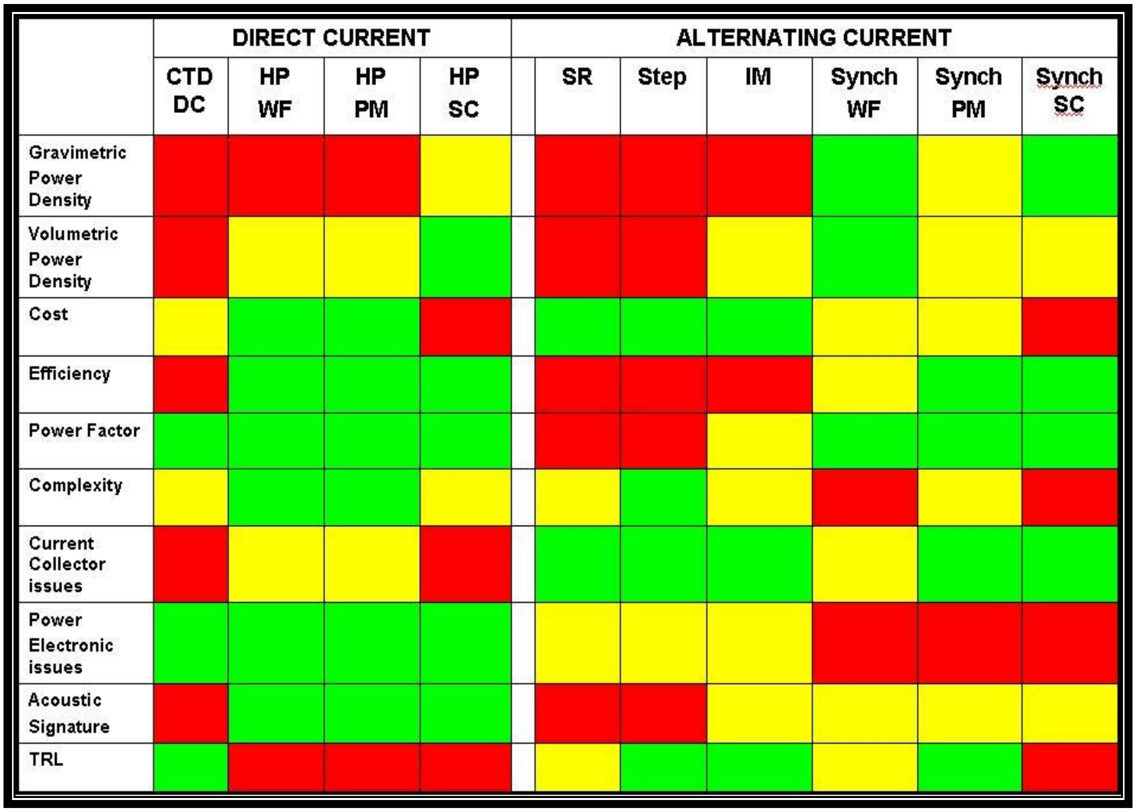
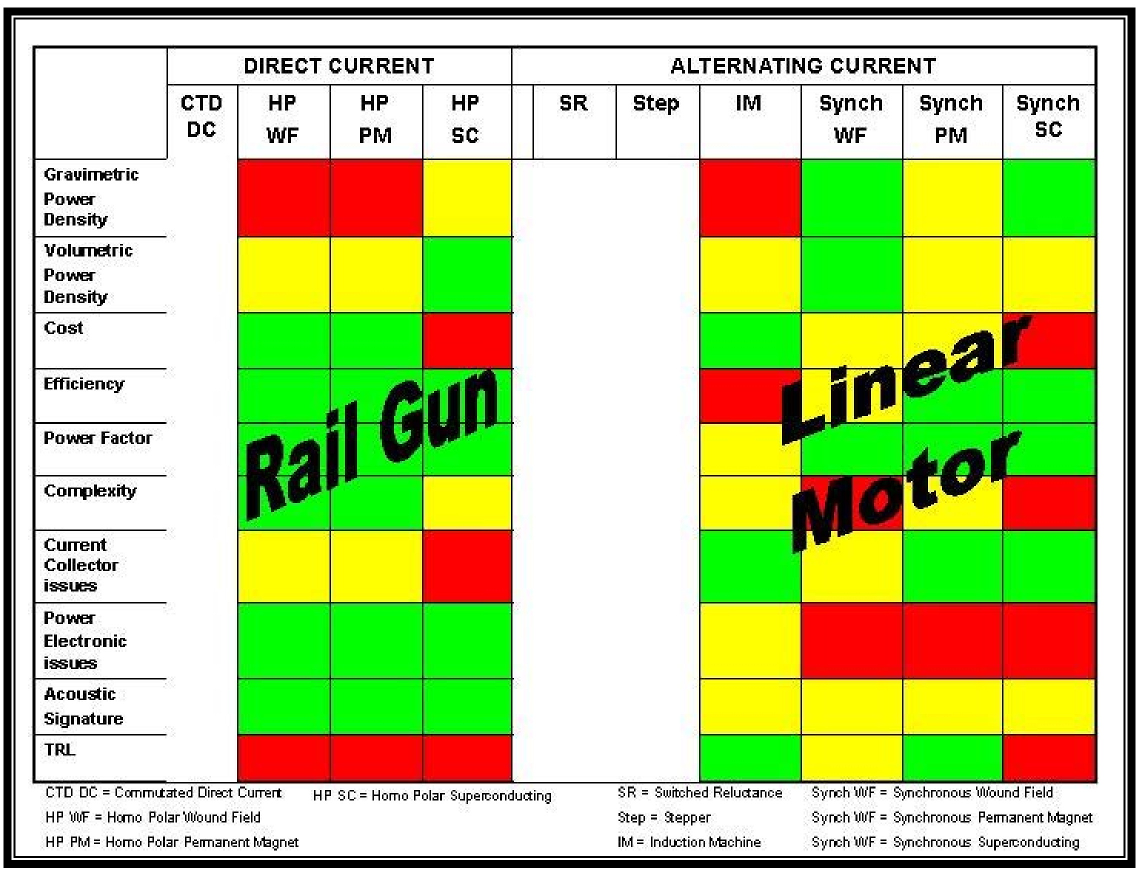


Figure 9 – Linear Actuator Motor Topologies

Table 4 – Motor System Characteristics





As a result of the preliminary analysis, linear motor and rail gun technologies were indicated as worthy of further evaluation. Linear motors are a relatively mature motor class technology and can be seen today in operational concepts used on state-of-the-art roller coasters. They have also been included in preliminary EMALS / EARS launch system designs; however, ALDS launcher system accelerations and path will impact the scaling of any EMALS results.

Rail gun technology was also considered for use in the ALDS launcher system although it is presently an immature technology. Current S&T efforts in this area are focused on relatively small payloads at huge accelerations. Consequentially, the scalability to an ALDS payload and g loads will require further investigation since this technology requires a new application of fundamental principles to a high mass low speed application.

Energy Storage System Options

Chemical, mechanical and electrical energy storage options were identified and examined for possible use in the ALDS Launcher System. Similar to the linear actuator assessment, a preliminary evaluation technique was used to rule out unfavorable characteristics and highlight energy storage devices requiring further investigation. In this assessment, eight energy storage options were evaluated against eight functional areas: Power Density, Energy Density, Efficiency, Cost, Complexity, Power Electronic issues, Acoustic Signature, and TRL. The qualitative results are presented in matrix form in Table 5 – Energy Storage Technology Characteristics. Favorable characteristics are highlighted in “green” and least favorable combinations are depicted with “red “squares.

Table 5 – Energy Storage Technology Characteristics

	NiMH Battery	Lithium Battery	Ultra Cap	Flywheel	Super Cap	Cap	Pulsed Alternator	SMES
Power Density								
Energy Density								
Efficiency								
Cost								
Complexity								
Power electronic issues								
Acoustic Signature								
TRL								

Power Electronics Technology Options

The preliminary power electronics technologies evaluated included uncontrolled (diode) rectifiers, thyristor controlled rectifiers, and pulse-width modulated rectifiers; line commuted, 2-level PWM, and multi-level PWM inverters; and cyclo-, matrix and multi-port converters. Switch options for the technologies listed above and for Pulse Forming Network included IGCT's and IGBT's, etc. Each technology was evaluated against seven qualitative parameters: Gravimetric Power Density, Volumetric Power Density, Cost, Producibility, Efficiency, Power Factor/Power Quality, and Technology Readiness Level (TRL). Results are shown in Table 6 – Power Electronics Technology Characteristics, where "green" is favorable and "red" is least favorable.

Table 6 – Power Electronics Technology Characteristics

Parameter	Diode Rectifier	Thyristor Rectifier	PWM Rectifer	Line Commutated Inverter*	2-Level PWM Inverter	Multi-level PWM Inv	Cyclo-Converter*	Matrix Converter	Multiport Converter
Gravimetric Power Density	Green	Green	Red	Green	Red	Red	Green	Green	Green
Volumetric Power Density	Green	Green	Red	Green	Red	Red	Green	Green	Green
Cost	Green	Yellow	Red	Green	Green	Green	Green	Red	Yellow
Producibility	Green	Green	Yellow	Red	Yellow	Yellow	Red	Red	Red
Efficiency	Green	Green	Yellow	Green	Yellow	Yellow	Green	Yellow	Green
Power Factor/ Power Quality	Red	Yellow	Green	Red	Yellow	Green	Red	Green	Green
TRL	Green	Green	Yellow	Green	Green	Yellow	Green	Red	Red

* Insufficient output frequency capability

Linear Motor Considerations

A review of the specifications for the EMALS motor design was performed to make a decision for the choice of linear motor to be used for the ALDS design [4]. Three different motor types and two primary coil connection configurations were considered:

- Linear induction (LIM)
- Linear permanent magnet synchronous (LPMSM)
- Linear bulk superconductive magnet (LBSCMM).

In each case, each motor primary was connected in either a half phase per pole (HPP) or one phase per pole (OPP) configuration. Two temperature superconductor magnetic cases, 77K and 40K were considered for each LBSCMM motor case. A comparison of the rotor masses and power factors for each of the six (6) EMALS cases is presented in Table 7.

Table 7 – Data Comparison for Different Motor Topologies

Parameter	LIM HPP	LIM OPP	LPMSM HPP	LPMSM OPP	LBSCMM 77K	LBSCMM 40K
Pole Pitch (m)	0.265	0.650	0.072	0.074	0.084	0.084
Rotor Length (m)	4.24	7.80	5.64	7.38	6.38	2.35
Rotor Height (m)	3.31	3.96	2.14	2.13	2.14	2.14
Rotor Mass (kg)	2175	2070	2093	2104	2485	916
Stator Coil Inductance (μH)	3.077	0.840	0.924	1.215	0.052	0.052
Stator Coil Resistance ($\mu\Omega$)	37	9	120	160	114	114
Frequency for v=103 m/sec	204	83	712	698	613	613
Power Factor	0.504	0.106	0.671	0.642	0.999	0.999

The low temperature (40°K) linear bulk superconductive magnetic motor (LBSCMM) was chosen as the design of choice for the ALDS application. It provides the highest force vs. rotor weight required, allows much higher magnetic field generation than the linear induction or linear permanent magnet motors, and has a nearly unity power factor capability. For the upcoming discussion, a magnetic field intensity of 5 Tesla is used in an initial design specification of a superconducting magnet motor for ALDS. This is a realistic value based on current superconductor properties. In the future, superconducting magnets are expected to reach much higher intensity values which would be even more advantageous.

The geometry of a linear bulk superconductive magnetic motor (LBSCMM) is shown in Figures 10, 11, and 12.

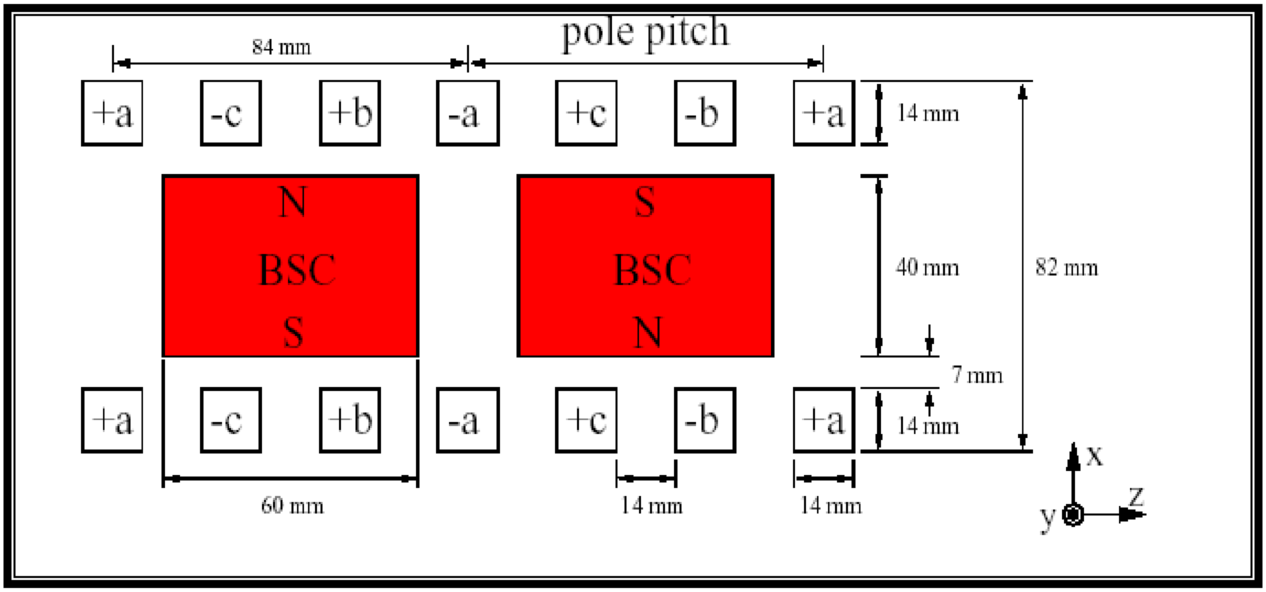


Figure 10 – Cross–section of a LSCPMM in x-z plane given for two pole pitches

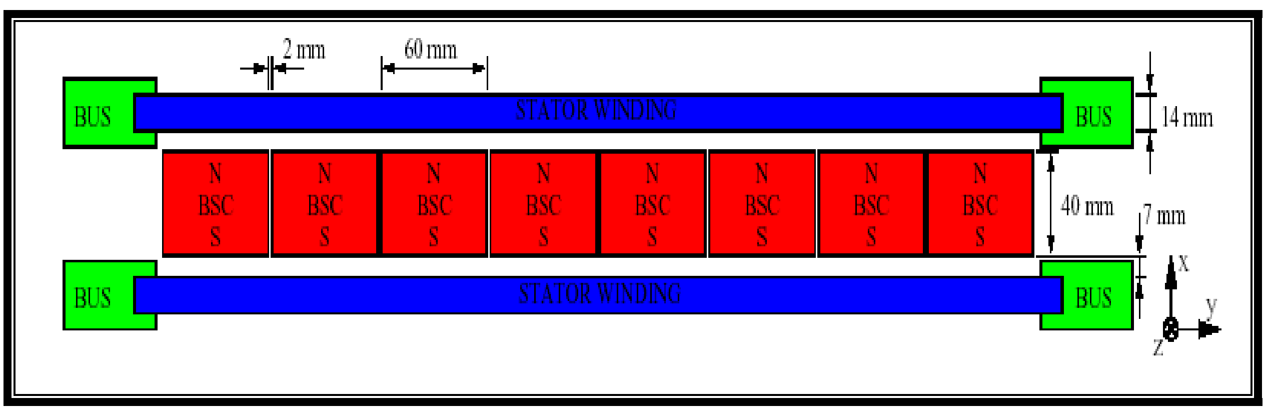


Figure 11 – Cross–section of the LSCPMM in x-y plane

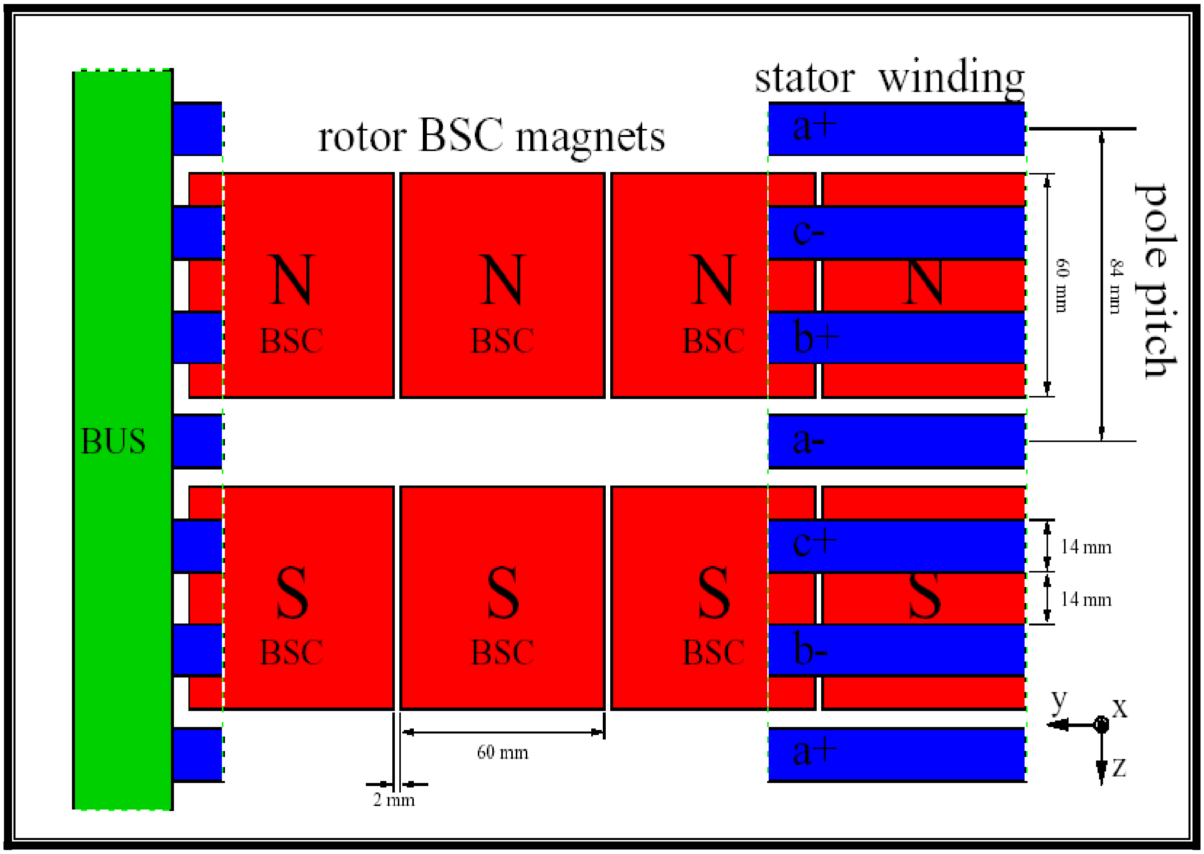


Figure 12 – Cross–section of the LSCPMM in y-z plane

Having chosen the linear bulk superconductive magnetic motor for the preliminary design, calculations need to be made concerning the shuttle's geometry, mass, number of pole pairs, and forces needed to meet system operating requirements. The maximum allowable shuttle weight was originally 200 kg, however, since cryogenic cooling of the shuttle is necessary, an additional 125 kg of weight for the cryogenics is now included. The total maximum weight is now 325 kg for shuttle and cryogenics. The new peak power requirement resulting from the additional weight of the cryogenics can be derived from Figure 13 – Revised Power Requirements. This new combined weight is referred to as the *shuttle* from this point on in the discussion.

Since payload and vehicle weigh is 681 kg, the new total weight needing to be accelerated to 257 meters per second is 1006 kg. An acceleration of 37.1 g, equaling 364 m/sec^2, is required for the case of the reusable shuttle design. Using the EMALS design and dimensions, a scaled version of the required shuttle can now be obtained. The half phase per pole (HPP) design is used based on ALDS launch data [2,3].

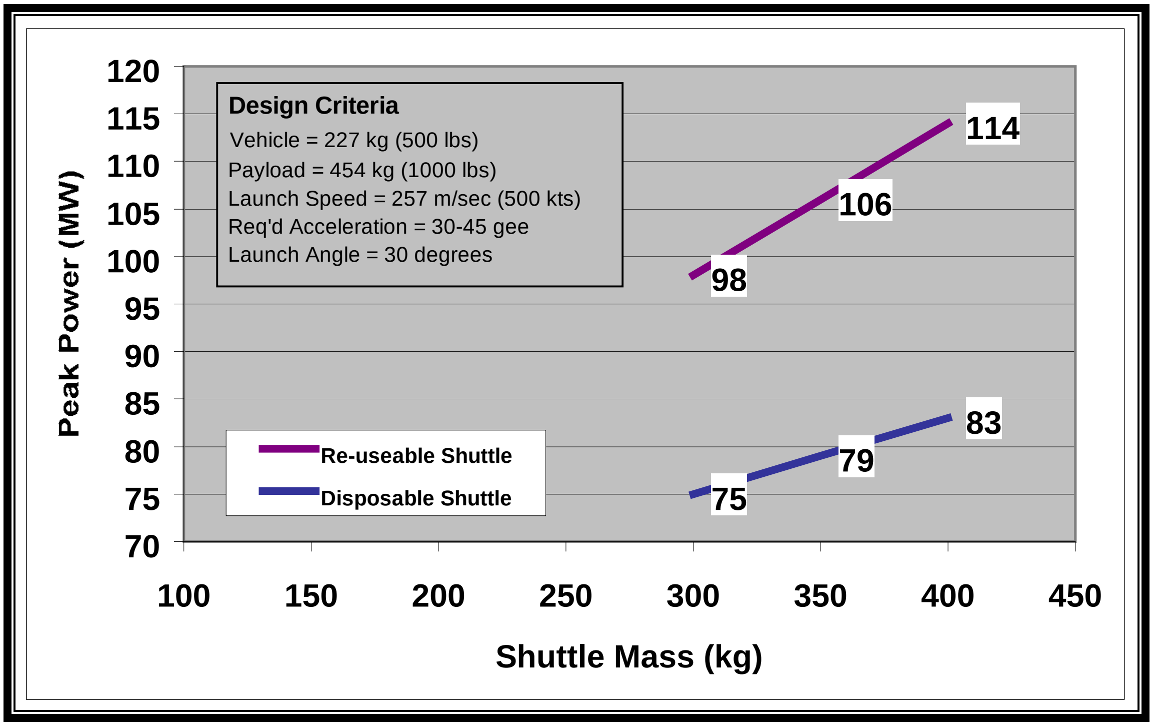


Figure 13 – Revised Power Requirements: Shuttle Mass versus Peak Power

HPP Design Data and Properties

The number of magnetic pole pairs required to produce the 365 kN of force is the biggest modification of the EMALS design for the ALDS implementation. Using the following relationship, ΔF is defined as the force per pole using yttrium barium copper oxygen (YBCO) superconducting material.

ΔF = J*A*B*Y where J = maximal current density in the superconductor, A = conductor cross sectional area, and Y = conductor length in y-direction. For this particular problem, we assume an input B of 5 Tesla for our magnet strength.

Using ΔF = J*A*B*Y, with $J = 3 * 10^7$ amperes / m^2, $A = (0.014\ m)^2$, B = 5 Tesla, Y = 0.492 meter. Therefore, ΔF = 7,200 N/pole or 14,400 N / pole pair. Since a 3-phase HPP system is also proposed, there will be 6 stator windings per pole pair. The number of pole pairs calculated for the design is 365kN / [(6)(14,400 N / pole pair)] = 4.16361 pole pairs. Therefore, we need to use 5-pole pairs of superconducting magnets to produce at least 365kn of thrust. The actual thrust produced with 5 pole pairs is 439kN.

Five (5) pole pairs of superconducting magnets require a shuttle length of 5*0.168 m equaling a total length of 0.840 m. Summarizing the requirements and specifications below, we obtain:

- **Initial Design Requirements for Superconductive Type**
  - Force: 365 kN for shuttle, payload, glider and 125kg of cooling equipment
  - Length: Rotor - 840 mm @ 5 pole pairs;
    Stator along full 111 meter total path length of shuttle

- **Derived Requirements** based on scaled version of EMALS approach
  - 5 Tesla magnetization
  - Rotor: 325 kg; 0.840m x 0.496m x 0.040m x 4 rotors = $0.0667m^3$
  - Stator: 26,155 kg; 18 m^3 (111m x 0.496m x 0.082m x 4)
  - Cooling equipment adds 125 kg to 4 rotors total weight
  - 6000 Amps, 9000 Volts, 3 phase $0 < f < 1530$ Hz
  - 7 mm air gap between rotor and stator poles
  - Maximum frequency of 1,530 Hz for $v = 257$ m/sec
  - Force predicted: 439 kN

- **Current Performance Requirements: 5 Tesla**
  - Cooling of superconductor to achieve required temp (40K)
  - Current density of 1000 A/mm^2 (YBCO – bulk material)

Linear Motor S&T Gaps

- **Technology State-of-the-Art (Present-2010):**

Extremely *high field* superconducting magnet technologies with *extremely low temperatures* are being investigated by the following organizations: (1) National Science Foundation - 21.1 Tesla at 1.7° K (13000 Kg), (2) National High Magnetic Field Lab - 45 Tesla with 2.2° K Helium, (3) American Magnetics - 17 Tesla with 2.2° K Helium using $Nb_3Sn/NbTi$, (4) Cryo Industries - 15 Tesla with 4.2° K cryocooler [5]. The bores of these magnets do not exceed 105 millimeters and can weigh upwards of 15 tons. Low capacity pulse tube cryo-coolers with high g endurance have been developed for NASA in the 4°K to 80°K range.

- **Next Navy: 2010-2020**

The goals for high amplitude magnetic capabilities in the midterm are to develop: (1) Pulse tubes with hundred to kilowatt cooling capacities in the 80°K temperature range, (2) Pulse tubes capable of kilowatt range cooling under *high g force* endurance in 80°K range; and (3) *Very low* temperature cryogenic coolers with *kilowatt cooling capacities* and *high g force* endurance.

- **Navy After Next: 2020-2030**

High temperature material research and high field magnet design capabilities should be stressed in the long run. Ideally, large bore, 0.5 meter, magnets having fields upward of 20 Tesla at 80°K are desired. In addition to this, superconducting material research to reduce the AC loss and allow use of the superconducting material in the stator of the motor would be beneficial.

High field, large bore magnets are an ongoing research topic, at NRL, ORNL, LANL, BNL, DOD, and various universities. In the area of reduced AC losses in superconductors, the DARPA SuperHype program with NRL, American Superconductor, ORNL, and NSWCCD are actively performing research. High field magnets with bore sizes greater than 0.5 m are long-term objectives at NHMFL, MIT Magnet Lab, and the LANL.

Pulse tube research involving two long term research capacities are: (1) DOE cryogenic program to develop 1 kW cooling capability in the 80° K range, for HTS 2004-2006 programs in a CVN-21 1.2 kW @ 77° K system for LN_2O_2 production; (2) *Very low* temperature cryogenics combined with *kilowatt power*, an NSWC 2005 ILIR Proposal for Low Temperature Pulse Tubes. A very far term goal would be a kilowatt size Pulse Tubes in a high gee environment. There are no efforts ongoing in this area of study.

Rail Gun Considerations

Rail Gun Performance Requirements and Design Options

The ALDS performance requirements and design parameters applicable to the assessment of the rail gun technology are summarized below:

- Shuttle + Payload + Glider = 881 kg. (2000 lbs max)
- Maximum velocity = 257 m/s (500 kts)
- Required acceleration = 30 g
- Track Length = 111.69 m (365.0 ft)

Derived requirements and design options are provided in the following analysis.

The acceleration of the 2000 lb. package (881 kg) to a velocity of 500 knots (257 m/s) with a track of length 365.0 ft. (111.69 m.) requires a constant force of 264,000 Newtons.

The electromagnetic force (refer to Figure 14 – Composition of a Rail gun) developed in a rail gun is calculated according to the following relationship:

$$F_{EM} = \frac{1}{2} L' I^2$$

where: L' is the inductance gradient, the rate of change of the circuit inductance per unit displacement of the armature, and I is the DC current through the gun circuit.

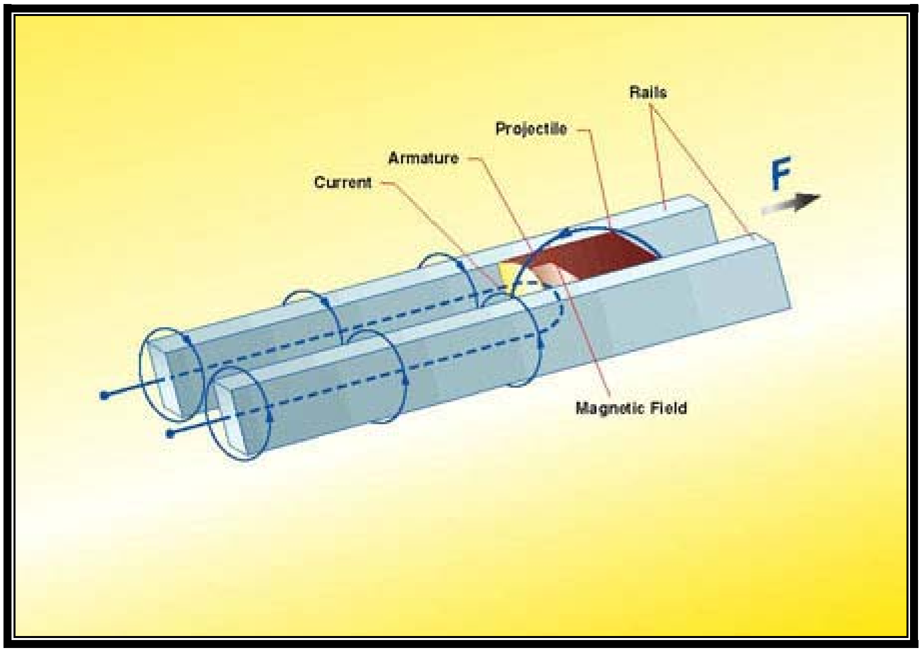


Figure 14 – Composition of a Rail gun

Assume rails with a height of 50 mm, width of 20 mm, and rail separation of 70 mm. These dimensions are typical for rail gun systems. For this rail geometry, the estimated inductance gradient is $L' = 0.6050$ μH/m. The required current for these rails would be:

$$I = \sqrt{\frac{2 \cdot F_{EM}}{L'}}$$

$$= \sqrt{\frac{2(264000)}{0.6050(10^{-6})}}$$

$$= 9.34198 \times 10^5 \text{ amps}$$

This is an acceptable figure for most purposes, and the current density in the rails is acceptable and consistent with current design practices, so this may be taken as a design value.

This current can be developed in two counter rotating pulsed alternators, which will balance the torque reactions to a substantial degree, but not quite perfectly, with each machine current at approximately 467,099 amperes, probably an acceptable design.

Consider the energy to be delivered, and then work backward to estimate the energy required from the pulsed alternator, the muzzle energy required is:

$$\begin{aligned} T_{final} &= \frac{1}{2} M_T V_f^2 \\ &= \frac{1}{2}(881)(257.22224)^2 \\ &= 2.91 \times 10^7 \text{ J} \\ &= 29.1 \text{ MJ} \end{aligned}$$

This is at best half the energy in the system at that moment, so the total energy in the system at that instant is at least 58.2 MJ.

If we optimally assume a system efficiency of 50%, this indicates that 116.4 MJ from the pulsed alternator is required. The discharge time interval is 0.856 sec, so the average discharge power is 116.4 MJ over 0.856 second, requiring 136 MW power. Navy machines run in the speed range 6500 to 8000 rpm. The size of the rotor required to store half this much energy from this speed drop is:

$$2 \cdot \frac{1}{2} J(\omega_1^2 - \omega_2^2) = 2 \cdot 2 \cdot T_{final}$$

This calculation allows for the fact that twice the energy stored in the system is necessary to get to the 58.2 MJ requirement. It then permits a 50% conversion efficiency while including the speed drop of both machines.

Adjusting this to put it in terms of the machine speed in rpm, and solving for the rotor mass moment of inertia gives:

$$J_{TotalRotor} = \frac{2 \cdot 2 \cdot T_{final}}{\omega_1^2 - \omega_2^2} = \frac{4 \cdot T_{final}}{\left(\frac{2\pi}{60}\right)^2 (N_1^2 - N_2^2)} = \frac{4 \cdot 30 \cdot 10^6}{\left(\frac{2\pi}{60}\right)^2 (8000^2 - 6500^2)} = 503.11 \text{ kg–m}^2$$

This is the total rotor inertia, and will be split between the rotor of the pulsed alternator and the rotor of the drive motor. The rotors will be made integral with each other (i.e. on the same shaft, in the same housing).

For a conservative design, let the tip speed be held below 400 m/s, so that

$$R_{Max}\omega_1 = 400 \text{ m/s}$$
$$R_{Max} = \frac{400}{\omega_1} = \frac{400}{\frac{2\pi}{60}8000} = 0.477 \text{ m}$$

To obtain the required alternator rotor mass moment of inertia with a right circular cylindrical shell of radius, let R_{out}= 0.45 m and R_{in}= 0.35. Considering the previous calculation:

$$\begin{aligned} Area &= \frac{\pi}{4}(D_{out}^2 - D_{in}^2) + \frac{\pi}{4}D_{Shaft}^2 \\ &= \frac{\pi}{4}(0.9^2 - 0.7^2) + \left(\frac{\pi}{4}\right)(0.120^2) \\ &= 0.26264 \text{ m}^2 \end{aligned}$$

Carbon fiber composite laminate has a mass density of approximately 1660.8 kg/m^3, and the mass density of the aluminum windings is approximately 2712.3 kg/m^3. There is also a large shaft to be considered, probably made of steel, and 0.120 meters in diameter. The density of steel is 7800 kg/m^3.

The average density of the cross section will be, approximately:

$$\rho_1 A_1 = (1660.8)\left(\frac{\pi}{4}\right)(0.9^2 - 0.87^2) = 69.263$$
$$\rho_2 A_2 = (2712.3)\left(\frac{\pi}{4}\right)(0.87^2 - 0.82^2) = 180.0$$
$$\rho_3 A_3 = (1660.8)\left(\frac{\pi}{4}\right)(0.82^2 - 0.7^2) = 237.92$$
$$\rho_4 A_4 = (7800)\left(\frac{\pi}{4}\right)(0.120^2) = 88.216$$
$$\rho_{Avg} = \frac{\sum \rho A}{Area} = \frac{69.263 + 180 + 237.92 + 88.216}{0.26264} = 2190.8 \text{ kg/m}^3$$

Based on this average value for density, and an assumed length of 1.5 m, the value of J is

$$\begin{aligned}
\frac{J_{Alt}}{\rho l} &= 4.0841 \times 10^{-2} \\
J_{Alt} &= 2190.8(1.5)(4.0841)(10^{-2}) \\
&= 134.21 \text{ kg–m}^2
\end{aligned}$$

The alternator rotor inertia (for pulsed alternator and shaft) will have a mass of

$$\begin{aligned}
M_{Alt} &= \frac{\pi \rho l}{4}(D_{out}^2 - D_{in}^2 + D_{Shaft}^2) \\
&= \frac{\pi(2190.8)(1.5)}{4}(0.9^2 - 0.7^2 + 0.12^2) \\
&= 863.09 \text{ kg}
\end{aligned}$$

The balance of the mass moment of inertia (MMOI) will be in the rotor for the recharge motor. This will be an iron core motor, and there will be no difficulty at all in supplying the rest of the required MMOI between the rotor bars (or windings, depending on machine type), and the laminations.

This is not a disproportionate machine, so it can be taken as a reasonable first cut rotor design. If the rotor diameter D_{out} is 0.9 meters, then the stator outside diameter will be on the order of 1.2 meters. The rotor length is 1.5 m, as specified in the above calculations, so the overall machine length is probably close to 2.0 meters. These will be two, sizeable machines.

The estimates above give some idea for the size of the alternator itself. It does not address the power electronic components, nor does it consider in any way the support systems such as cooling and anything else required. For systems existing today, the complete systems are much bigger than just the alternators.

This option looks desirable; however, a few of the extremely difficult problems that will be encountered if this approach were used are discussed below.

Rails: It will be necessary to design a system of rails that will be structurally supportable in the space of the shuttle, while transferring nearly a million amperes at perhaps 10,000 volts. There are extremely large forces trying to separate the rails, and holding them in place and in alignment has been one of the major problems for research guns to the present date.

Armature: It will be necessary to design an armature to move between the rails, conducting current from one rail to the other and sliding along the rails as the system accelerates.

Additional issues are discussed below:

a) If the accelerating armature is supposed to drive the shuttle, it will be necessary to connect the two. This poses serious problems since no one has even considered trying to maintain rail alignment with one side of the rails open as would be required to have access to the armature with the rails spaced at a few inches as in the usual configuration.

b) It could be argued that the rails will be placed far apart, with the complete launch package between the rails, placing the rails the better part of 10 feet apart. This would solve the problem of attaching the launch package to the armature. This is not at all realistic because of (1) to maintain tight alignment tolerances over such a large distance is far more difficult, and (2) it is far more difficult to get the required support stiffness on this much larger spacing to resist the separating forces that will be encountered. In this last regard, uneven structural stiffness will result in distortion of the rails even if the forces on the rail are uniform.

c) Curved Rail: The idea of trying to maintain the required electrical contact, without undergoing transition to a plasma arc contact that eats away the rail surfaces very quickly, while transiting the circular arc will pose new and exciting challenges that have not been previously studied. The radial side load will add interesting challenges to this problem, something that has not been explored.

d) Thermal Management: No one has demonstrated continuous repetitive duty for a pulsed alternator/rail gun system at the present time. It is known that there is substantial heating in pulsed alternators in single shot operation, and serious cooling is expected to be required in order to make repetitive operation possible. The pulsed alternator for the duty cycle described, repeated firing at frequent intervals hour after hour is far beyond the scope envisioned in even the most advanced research program today.

Derived requirements* are summarized below:

- Total required current: 934.2 kA (467.1 kA per track)
- Inductance per meter: 0.6050 mH
- Muzzle Energy: 29.1 MJ
- Average Power: 136 MW based on 0.856 sec. acceleration

* Rail assumptions: 50mm height, 20mm width, and 70mm separation

Rail Gun S&T Gaps

- **Technology State-of-the-Art (Present-2010):** ***Status of Rail Gun Development***

Rail guns [7] are currently being pursued by the US Army as a weapon for land combat vehicles due to their ability to impart extremely high velocities (to 4.5 km/s) to low mass projectiles (<10kg). Rail guns are also being pursued by the US Navy for shipboard surface fire support since electricity for the railgun could be supplied from an on-board compulsator, which in turn could be powered by the ship's engines [7,8,9]. Although full scale guns with linear barrel designs less than 12 meters long have been built and fired, including a very successful 90 mm bore, 9MJ kinetic energy gun developed by DARPA / University of Texas' Centre for Electromechanics [10], designs are currently experiencing extreme rail damage. Rail and insulator ablation issues still need to be addressed before railguns can be developed for an ALDS application. Additional research efforts are addressing energy storage, switching systems (currently vacuum arc switches), and thermal management of high-speed rotors.

To accelerate transformation of this technology, Commander, Fleet Forces Command has approved an 1/8th-scale rail gun demonstration in a Future Naval Experiment. The Sea Trial 21 Full-scale naval rail gun proof-of-concept demonstration was proposed for fiscal year 2008 [9].

- **Next Navy (2010-2020):** ***1st Generation Naval Rail Gun***

Based on future development of the ***1st Generation Naval Rail Gun***, features should include counter-rotating compulsators storing several hundred megajoules, a multi-stage launcher configuration designed to reduce rail ablation, and the use of SiC solid-state devices for more compactness with reduced losses. Using near term compulsators, system efficiencies are expected to be in the 35-45% range for converting rotor energy to kinetic energy. Muzzle velocities should approach 2.5km/sec (Mach 7.5) and muzzle energies should exceed 60MJ. With this capability, a projectile with a mass of approximately 10kg would reach a destination over 200 miles.

- **Navy After Next (2020-2030):** Projected mature rail gun technology should provide muzzle velocities up to 6km/sec, muzzle energies up to 300MJ, and firing rates of 6 rounds / min.

Rail Gun Summary

There are many concerns with using a rail gun as the actuator in the ALDS Launcher System. One of the primary issues is that nearly two decades of EM gun system technology development efforts have been geared towards land combat vehicles weapons and a myriad of fundamental issues like the use of a curved versus a straight rail design have not been addressed. Programmatic issues may also surface since the Most compelling application for EM guns in the future Navy is for surface fire support. Although the Navy can leverage Army rail gun research, fielding an ALDS launcher using rail gun technology requires a unique investment in a larger scale system. This will necessitate a development effort change from the current high speed (4^{+}km/sec muzzle velocity), low mass (projectile) system to a high mass (ALDS launch body)

comparatively low launch speed (0.25 km/sec) design. From a near-term perspective, the rail gun launcher is not feasible an alternative as the EMALS type launcher. In the mid/long-term however, an ALDS launch capability using rail gun technology could be a viable option if a parallel effort to the offensive weapon application is undertaken in the near term [7-13].

Energy Storage Considerations

Stated Requirements	**Derived Requirements**
(Based on mechanical kinetic energy)	(based on 75% efficiency)
– 100 MW Peak	– 43.7 MJ (linear increasing load)
– 0.656 Seconds	– 66.7 MW Average (linear increasing load)
– Constant torque	– 12.3 KWH
– <<207 Metric Tons	– 94.3 MW (equivalent pulse)
– <<237 Cubic Meters	– 0.46 Seconds (equivalent pulse)
	– <55 Metric Tons
	– <69 Cubic Meters

Energy Storage Device Characteristics and Selection

The linear motor for the ALDS Launcher system requires an input power that varies approximately linearly with speed as the shuttle and its load are accelerated down the rails. It is accelerated over an 84-meter track to a velocity of 500 knots in 0.66 seconds using 43.7 MJ or 12.15 kWh of electrical input energy with a peak power requirement of 133 megawatts given an efficiency of 75%. For energy storage device characterization, a rectangular pulse of the same area and equivalent resistive losses is used as an equivalent approximation. This pulse has a magnitude of 94.3 MW and duration of 0.46 seconds. The system requires 45% as much power as the EMALS system, therefore based on this energy storage system, weight of 55 metric tons and volume 69 cubic meters are estimated. This corresponds to a modest energy density requirement of 0.22 WH/kg and 0.18 WH/Liter. The peak power requirement is more significant for this application. It requires 1.7 kW/kg and 1.37 kW/Liter.

Figure 15 and Figure 16 are gravimetric and volumetric Ragone plots, respectively, that provide comparisons of the energy density and power density capabilities of various types of energy storage devices. Also included are discharge times (E/P) and figure of merit (E*P). Devices in the light green shaded portion of the plots meet the specifications for the ALDS Launcher System application. A fuel cell such as the alkaline type used in the Space Shuttle has superior energy density but far too little power density for this application. Other types of fuel cells for commercial applications are under development, however their capabilities should all be within a similar order of magnitude. Figure 17 and Figure 18 include rough-order-of-magnitude (ROM) estimates of candidate energy storage systems for the ALDS Launcher system application.

A wide variety of batteries including Lead Acid and Lithium Primary are available, but most do not provide the required power density. Some types of batteries such as High Power Lithium Ion or Lithion designed for pulse power applications may be suitable for such a launcher application. A small thin metal film lead acid battery originally produced by Bolder Technologies, which was acquired by GP new products, is designed for a very compact car jump starting application. A scaled up version with a smaller projected mass and volume than any other system considered in this study could hypothetically perform very well in the ALDS application.

A Mobile Flywheel Power Module or a bank of Ultra-Capacitors could be suitable for the application. Both systems are power limited and therefore are capable of delivering multiple launches. Each has a long cycle life. The flywheel is rated for a nominal voltage range that should be compatible with a drive system suitable for ALDS. The energy storage of the ultra-capacitor is de-rated by 33% so that it has at least 50% of its full state of charge voltage at the end of discharge. The flywheel is a relatively high voltage device therefore few units are needed for a system. It may have a safety issue because of its high operating speed or it could be subject to damage by shock and vibration encountered in the shipboard environment. The Super Capacitor is a small device similar to an ultra capacitor with higher power density. If it could be scaled to a larger size it could provide an energy storage system with a mass and volume much smaller than that an ultra capacitor. Both batteries and ultra capacitor banks are made up of low voltage cells, therefore large numbers of such units are needed for an energy storage system for ALDS and individual cell voltage and temperature management sub-systems are also likely to be needed. Finally the energy density of electrolytic capacitors such as BHC and other electrostatic capacitors is too low for this application.

Re-examining Figure 18 and considering the required discharge time of less than one second, the two primary candidate energy storage technologies are ultra capacitors and flywheels. Abridged descriptions and pictures of each are provided in figures 19, 20.

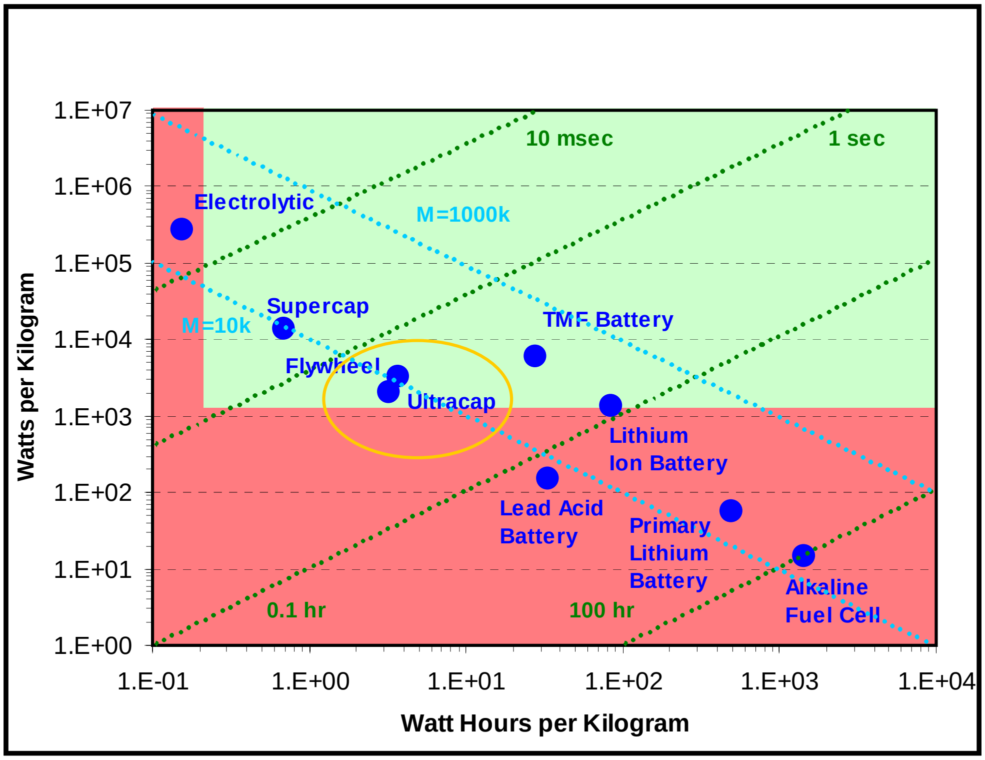


Figure 15 – Gravimetric Energy and Power Density

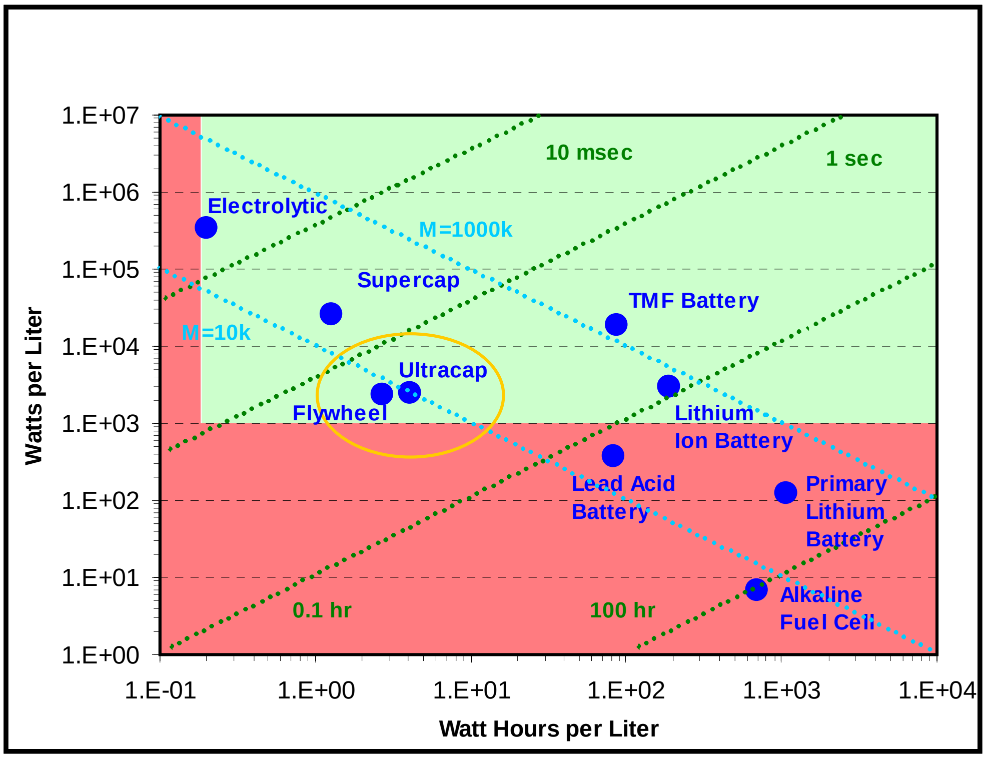


Figure 16 – Volumetric Energy and Power Density

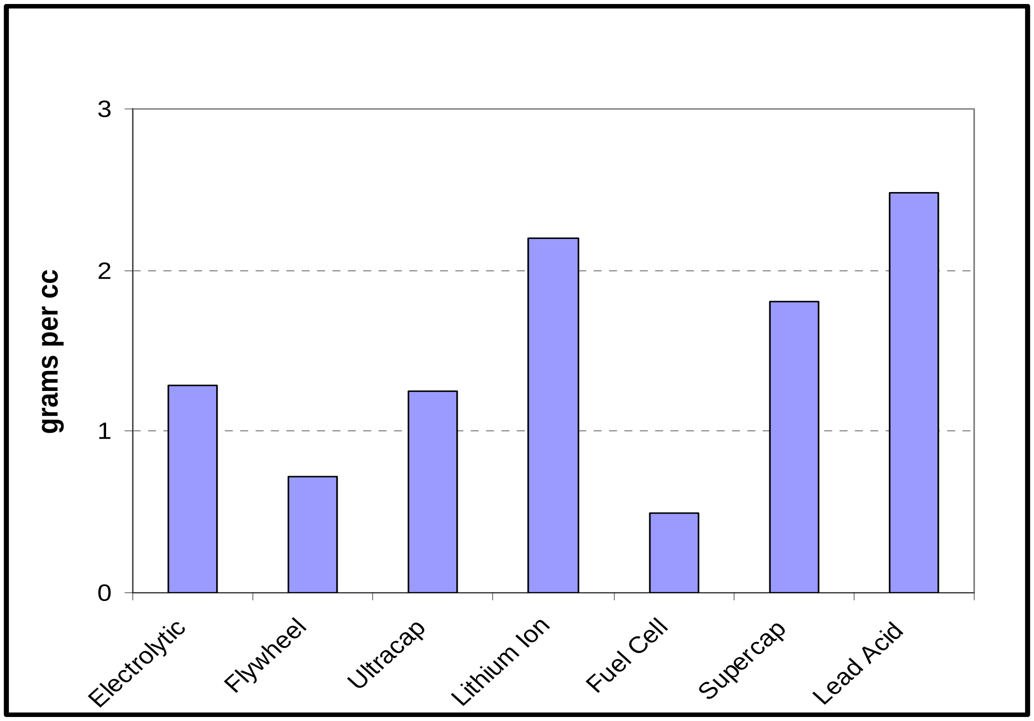


Figure 17 – Energy Storage Device Specific Gravity

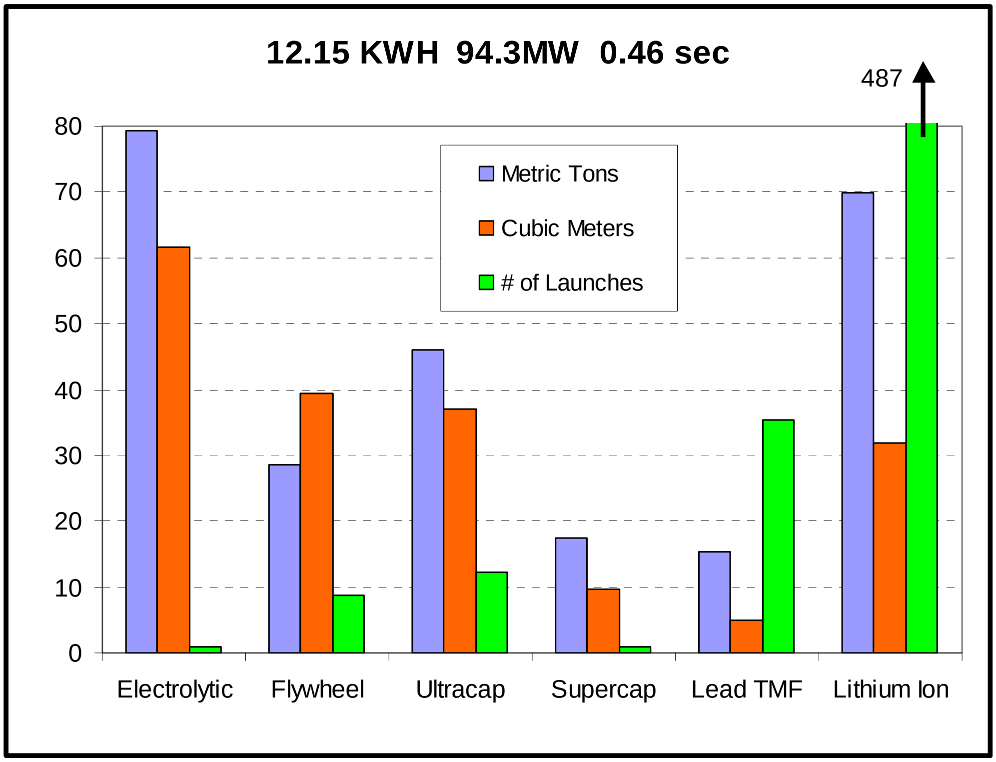


Figure 18 – Energy Storage Device Mass, Volume and Performance

Ultracapacitor. An ultracapacitor [13] (Figure 19) is a static DC device requiring simple power electronic interfaces. Ultracapacitors have a significantly higher energy density than electro-static or electrolytic capacitors and can be used as replacements for batteries in applications where a high discharge current is required. They can be recharged hundreds of thousands of times, unlike conventional batteries which last for only a few hundred or thousand recharge cycles. Pulse power batteries could also be considered because each launch uses less than 0.3% of a full discharge cycle.

Figure 19 – Example of an Ultracapacitor and High Power Battery Cells

Flywheel. A flywheel [14] is a heavy rimmed rotating wheel used to store kinetic energy. This mechanical device (Figure 20) stores energy efficiently (high turn-around efficiency) and has the potential for very high specific power compared with batteries. Flywheels also have a very high output potential, relatively long life, and are relatively unaffected by ambient temperature extremes.

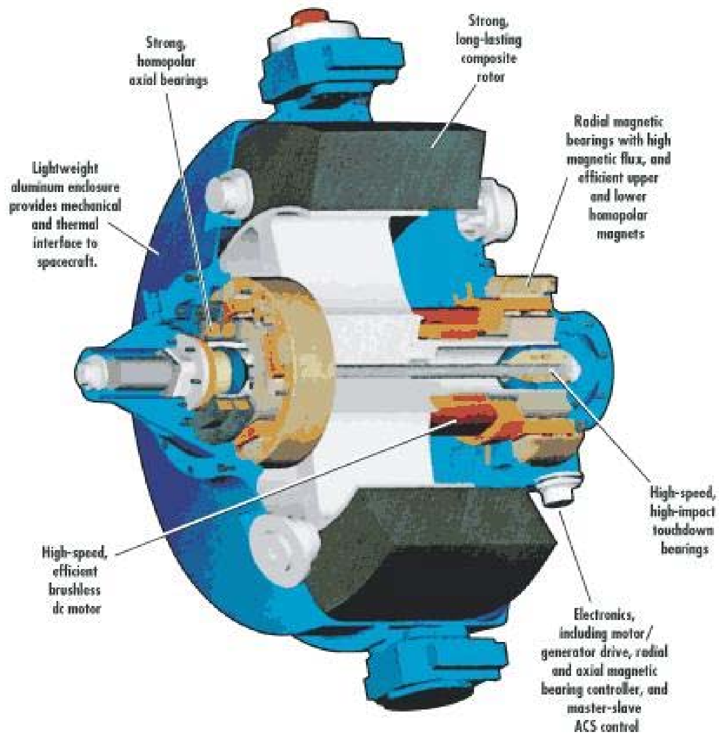


Figure 20 – Example of a Flywheel

Energy Storage S&T Gaps

Although capacitors and flywheels are the two primary candidates of choice for the ALDS Launcher system energy storage, each has specific issues that must be addressed. Capacitors (or ultracapacitors) require cell voltage equalization management and flywheels have safety concerns due to their high speed. They both have lower output voltage at end of cycle when highest drive voltage is needed. Although batteries or fuel cells would provide less voltage variation, lithium ion batteries would require cell voltage equalization management and batteries have a limited shelf life. Fuel cells could serve as a more efficient prime mover but would require a significant advancement in the technology to be useful for the ALDS Launcher system application in the near term.

The near-term outlook for energy storage technologies includes improved power density batteries and the option to scale up the size of supercapacitors. In the long term we could expect a general improvement in power densities, fuel cell possibilities using nano-technology, and improved energy density capacitors.

Power Electronics Candidates

Stated Performance Requirements

The stated performance requirements and design parameters used in the assessment of ALDS power electronics options are provided as follows:

- Integrated Controls for the complete Power Electronic system
- 100 MW Peak Power
- Constant Force (Constant Current)
- Efficiency High 90's

Derived Requirements and Performance Characteristics

Derived requirements, considerations and performance characteristics are provided below:

Derived Requirements

- Superconductive linear motor requirement - 3 phase, 5880 Amps rms, 9000 Volts rms,
- $0 < f < 1530$ Hz fundamental frequency
- Power Factor Control – 0.999 p.f.
- Power Regeneration by Braking Shuttle

Considerations:

- Physical Dimensions ROM can be based on 50% volume of COTS equipment
- Converter Thermal Management, De-ionized Chilled Water

Performance Characteristic

- Switching Frequency 10-100KHz
- Rated Switch Voltage 13kV-15kV (DC Blocking 6.5kV-7.5kV)

Candidate Power Electronics

The following describes the methods used and results obtained for calculating a rough order of magnitude estimate of the power electronics required to convert electrical power from an electrical source to a variable voltage, variable frequency waveform suitable for a linear motor used to propel a launch body the appropriate velocity to meet the application requirements. In this exercise the following assumptions were made:

Power conversion would be needed to convert fixed frequency electrical generator power to variable frequency/voltage electricity to spin up a rotating energy storage device. Based upon

the launch repetitive rate required and the total launch energy required, this power converter needed to be sized to 0.27MW.

Power conversion would be needed to convert the slowly decreasing voltage/frequency energy storage electricity to a variable voltage/frequency electrical waveform to drive the linear motor. The peak power requirements of this motor are 100MW.

The power converter used to drive the linear motor would need to operate in all four electrical quadrants, i.e. it would need to both supply electrical energy to the linear motor during launch body acceleration as well as dissipate energy regenerated by the motor during armature deceleration. Braking resistors would be required to dissipate this regenerative energy.

Since there was not a lot of time given to performing this first estimate of the power electronics requirements, this particular effort relied upon extrapolating information available from existing designs having similar application. One design referenced in this exercise was the Electromagnetic Aircraft Launch System (EMALS) full scale, half-length engineering design model (EDM) developed by NAVAIR. The second design referenced was the ONR-sponsored COTS based EMALS technology insertion. This second effort actually employed the building block approach that ABB Inc. used to develop their EMALS technology insertion.

First method – NAVAIR EMALS EDM

The NAVAIR EDM was a 200MW power converter driving a linear induction motor with a variable voltage, variable frequency waveform from 34 to 120Hz, 0 to 1577Vrms Line to Neutral at 0 to ~40,000A. The topology selected in this application was a 3-level neutral point clamped inverter employing insulated gate bipolar transistors (IGBTs) as the power semiconductor switches. It also included a power converter that converted 60Hz generator power to a variable voltage/frequency to spin up a rotating energy storage generator.

Comparing power, voltage, current and frequency requirements of the EMALS design to those required for the ALDS design, it became apparent that it was possible to come up with a ROM estimate for the volume and weight of the power conversion equipment, since the ALDS power requirements fell below the EMALS requirements in most cases. A visual reference of typical power electronics equipment is provided in Figure 21– Power Electronics Equipment.

For some parameters, this exercise should result in a reasonable prediction. For others, there will be some difficulties as a result of the limitations of the state of the art. Voltage and current requirements for both machines are comparable and the ALDS converter should be able to meet these requirements with the present state of the art. The present ALDS linear motor design requires an output sinusoidal frequency of 1530 Hz. This is about 10 times higher than the EMALS application. It may be difficult to reach this frequency requirement employing the present drive/switch topology unless the ALDS motor/load combination can handle a high level of harmonics, which in turn would result in torque pulsations.

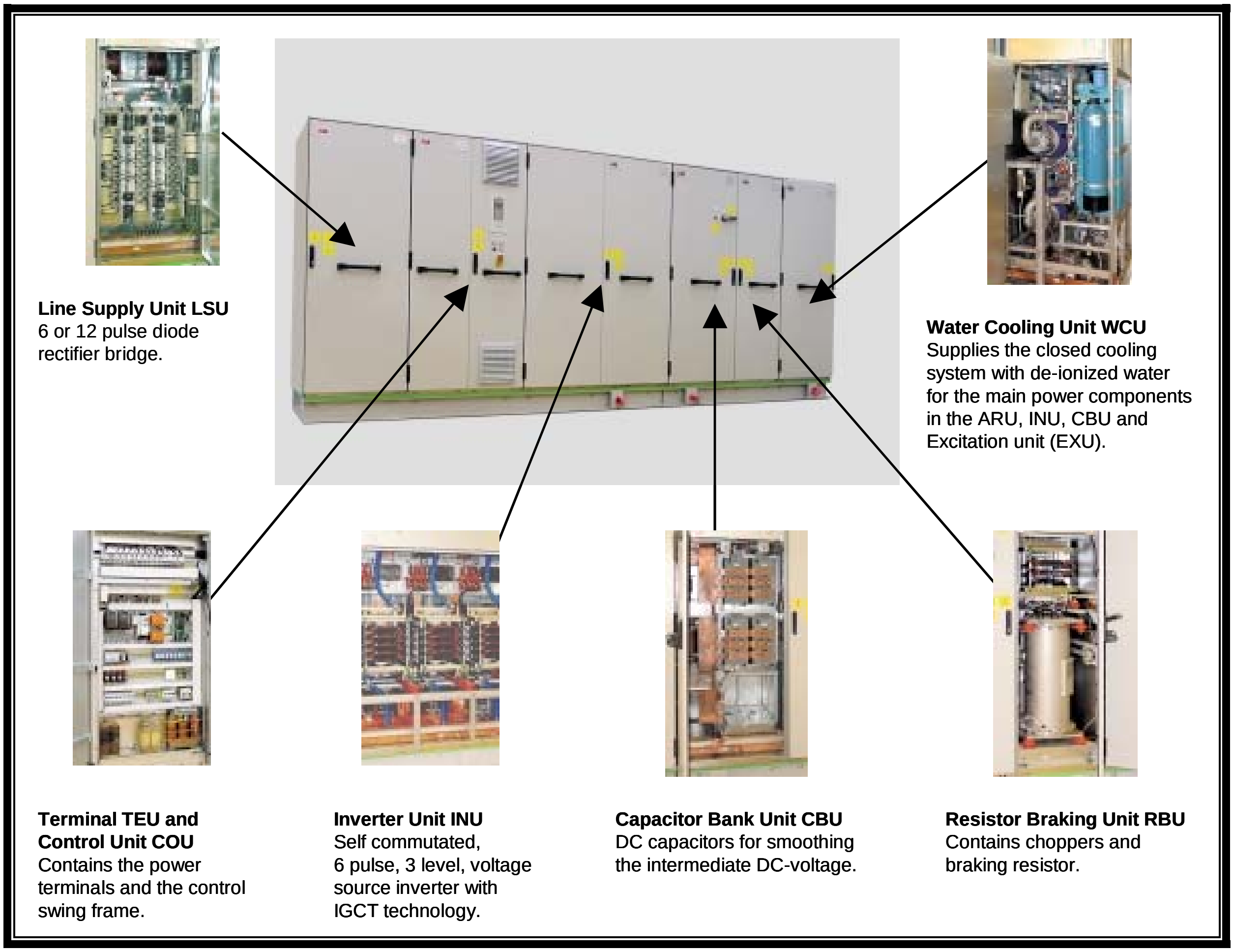


Figure 21 – Power Electronics Equipment

In Table 8 – Comparison of ALDS Launch Requirements with EMALS it can be seen that the ALDS design has energy requirements about $^{1}/_{5}$ of EMALS and power requirements around ½ of EMALS. Knowing that the power electronics components size and weight would be driven by the power requirements, it is assumed that the power electronics equipment needed for ALDS should be approximately ½ the weight and volume of the EMALS power electronics. A review of the EMALS design contract proposal showed that the EMALS design would come in at about 168 cubic meter drive volume and 53,000 kg drive mass. Multiplying these by ½ gives 83 cubic meters and 26000 kg for ALDS power electronics.

PARAMETER	ALDS				EMALS				ALDS/ EMALS Ratio
	Value	Units	Value	Units	Value	Units	Value	Units	
Launch Velocity	500	kts	257	m/s	200	kts	103	m/s	
Accel track length	276	ft	84	m	287	ft	87	m	
Glider Mass | Aircraft Load	500	lb	227	kg	50,707	lb	23,000	kg	
Payload Mass	1,000	lb	454	kg	0	lb	0	kg	
Total Mass w/o shuttle	1,500	lb	680	kg	50,707	lb	23,000	kg	0.03
Shuttle Mass	1,066	lb	325	kg	22,046	lb	10,000	kg	0.03
Total Mass	2,566	lb	1,005	kg	72,753	lb	33,000	kg	0.03
Launch Energy	17	M ft-lbs	23	MJ	90	M ft-lbs	122	MJ	0.18
Shuttle Energy	8	M ft-lbs	11	MJ	39	M ft-lbs	53	MJ	0.20
Total Energy	25	M ft-lbs	33	MJ	129	M ft-lbs	175	MJ	0.19
Source Energy	33	M ft-lbs	44	MJ	172	M ft-lbs	233	MJ	0.19
Efficiency	75%		75%		75%		75%		1.00
Peak Mechanical Power	136,580	hp	102	MW	275,507	hp	205	MW	0.50
Force	89,018	lb	0	MN	448,914	lb	2	MN	0.20
Average Mechanical Power	68,290	hp	51	MW	137,753	hp	103	MW	0.50
Average Electrical Power	38	M ft-lbs/s	68	MW	101	M ft-lbs/s	137	MW	0.50
Peak Inverter Power	138,278	hp	103	MVA	278,933	hp	208	MVA	
Ratio:Inverter Pwr to Avg Elec			2.3				1.5		
Equipment Volume - Energy Storage, Drive and Motor	9,253	ft^3	262	m^3	18,666	ft^3	528	m^3	
Equipment Mass	225	LT	229,038	kg	455	LT	462,013	kg	
Equipment Volume - Drive Only	2,948	ft^3	83	m^3	5,946	ft^3	168	m^3	
Equipment Mass - Drive Only	87,054	lb	26,534	kg	118,000	lb	53,524	kg	

Volumes are for components only and do not include requirements for access.

Table 8 – Comparison of ALDS Launch Requirements with EMALS

Second Method – ABB COTS hardware approach

This second method was employed to determine whether a commercial-off-the-shelf (COTS) – derived building block approach could be employed to meet the ALDS design requirements. In this exercise, the same philosophy employed by ABB was used for the ALDS design. That is, ABB has a set of datasheets describing building block power bridges, rectifiers, cooling units, braking resistors, etc. that can be stacked together in various configurations and power levels to meet multiple types of electrical power conversion applications (ACS6000 product line). Like the EMALS design, the ACS 6000 employs a 3 level neutral point clamped inverter to synthesize variable voltage/variable frequency output waveforms. The inverter bridge uses insulated gate controlled thyristors (IGCT's) as the power semiconductor switch instead of IGBTs. ABB manufactures the IGCTs themselves. ABB has successfully demonstrated this approach in building propulsion motor drives for ships, dynamic voltage restoration circuits for utilities, battery energy storage systems for uninterruptible power and various other applications at various MW power levels. The same building blocks were selected for the ALDS design to come up with a size and weight estimates. Table 9 - ABB ACS6000 Product Line shows the breakout of components one could select to perform the ALDS function.

The volume and mass for the COTS-based solution is about 1.5 times the result obtained using the EMALS hardware. The output frequency of the ABB components is presently limited to 250Hz, so it would run into the same limitations as the EMALS design for meeting ALDS output frequency. In addition, the ABB building block concept is presently limited to combining no more than 6 ARU's and INU's together. The ALDS would require 22 total ARU's and INU's.

Table 9 – ABB ACS6000 Product Line

Product	Symbol	MVA	W(m)	H(m)	D(m)	Qty for ALDS	Volume m^3
Line Supply Unit (Diode Rectifier)	LSU	9	0.8	2.9	1	0	0
Terminal Unit and Control Unit	TEU/COU		1	2.9	1	5	14.5
Active Rectifier Unit	ARU	9	1.5	2.9	1	11	47.85
Inverter Unit	INU	9	1.5	2.9	1	11	47.85
Capacitor Bank Unit	CBU		0.8	2.9	1	5	11.6
Voltage Limiter Unit/Resistor Braking Unit	VLU		0.7	2.9	1	5	10.15
Water Cooling Unit	WCU		1	2.9	1	5	14.5
							146.45
							Mass (kg)
							34860

Power Electronics Sizing Summary

A rough order of magnitude (ROM) sizing of the ALDS power electronics was derived from an investigation of the EMALS design and a review of COTS equipment specifications.

- 0.27MVA Rectifier/Inverter for Energy Storage Recharge ($^1/_{10}$ the size of EMALS)
- 100MVA Rectifier/Inverter for Linear Motor (½the size of EMALS)
  - 83 cubic meters, 26,000 kg (extrapolating EMALS design), 146 cubic meters, and 35,000 kg (using COTS Equipment Specs)

Power Electronics S&T Gaps

The summary of S&T gaps for the Power Electronics switching devices are summarized in Table 10 and Table 11 below. The most critical elements in each table are the switching frequencies since high switching frequency produces high power quality and low acoustic signature.

Table 10 – Switching Devices / Feature Availability

Parameter	*Current State-of-the-Art*		*Needed for ALDS*
	IGBT	IGCT	Device X
Controls	Simple PWM Gate Control	Simple PWM Gate Control	Simple PWM Gate Control
Power Rating	Less than 1MW per device - Series/Parallel combinations required for hi-power application	More than 1MW per device	More than 1MW per device - Specifically a higher Voltage Rating with a modest improvement in current
Power Quality	High Switching Frequency - More ideal waveform	Low Switching Frequency- Requires more parallel units to improve waveform quality (interleaving)	Very High Switching Frequency
Thermal Mgmt	Low Thermal Impedance - lower demand on Thermal Management System	High Thermal Impedance	Low Thermal Impedance
(IGBT) Insulated Gate Bi-Polar Transistor; (IGCT) Integrated Gate Commutated Thyristor			

Table 11 – Power Electronics Controls System Design

Parameter	*Current State-of-the-Art*	*Needed for ALDS*
	System Design	System Design
Controls	ABB PEC800 Matlab/Simulink Real Time Controller	Present Technology should suffice
Power Quality	250 Hz waveform is produced by IGCT switching at 1500Hz @ maximum power levels. (IGBT based system may get there but may be power limited)	1530Hz waveform would require ~15000Hz switching frequency @ max pwr levels.

Structural and Thermal Considerations

Performance Requirements

- **Stated Requirements**
  - Track must support shear force of 365 kN (propulsion)
  - Aircraft/track interface (bearing, skid plate, etc) must support 257 m/s relative velocity
  - Electronics junction temperature must not exceed 125 ºC
  - Cryostat surface temperature should not exceed 20-50 ºC

- **Derived Requirements**
  - Track must support normal force of 493 kN
  - Aircraft/track interface must support normal force of 333 kN
  - Power electronics peak power dissipation (assuming 98% efficiency) 1.6 MW
  - Power electronics total thermal energy dissipation 750 kJ

Baseline Track Configuration

During the initial analysis of the baseline track configuration several issues were revealed. The discontinuous track curvature leads to an impulsive moment applied at the straight/curved junction and the finite curvature at the end of the track results in the glider being launched with a 2 rad/s spin. With the launch velocity requirement of 500 knots (257 meters/sec) and a 350 ft radius of the curved section, the centripetal load at the point of departure is approximately 60g. Launching was determined to take less than a second due to the high acceleration.

Several alternate track designs were considered including a logarithmic spiral, a polynomial/linear design, a circle/poly/linear design, and a polynomial design in order to try to eliminate impulsive torque, launch spin and reduce centripetal loading. It was determined that a polynomial design, subject to the following minimum criteria would be used for further study:

- 110 m linear travel
- Track elevation of 5 m at end of track
- 30 º slope at end of track (first derivative)
- Zero curvature at end of track (second derivative)
- Zero jerk at end of track (third derivative)
- Slope, curvature and jerk are all zero at start of track (Cases 2-4)

The case-by-case constraints are summarized in Table 12 – Summary of Case Parameters.

Table 12 – Summary of Case Parameters

	Start of Track (x=0)				End of Track (x=110 m)			
	Elevation	Slope	Curvature	Jerk	Elevation	Slope	Curvature	Jerk
Case 1	y=0	y’=-1	Free	Free	y=5	y’=1/2	y’’=0	y’’’=0
Case 2	Free	y’=0	y’’=0	y’’’=0	y=5	y’=1/2	y’’=0	y’’’=0
Case 3	y=-20	y’=0	y’’=0	y’’’=0	y=5	y’=1/2	y’’=0	y’’’=0
Case 4	y=-8	y’=0	y’’=0	y’’’=0	y=5	y’=1/2	y’’=0	y’’’=0
Case 5	Free	y’=0	y’’=0	y’’’=0	y=5	y’=1/2	y’’=0	y’’’=0
Case 6	y=-11	y’=0	y’’=0	y’’’=0	y=5	y’=1/2	y’’=0	y’’’=0
Case 7	y=-11	y’=0	y’’=0	y’’’=0	y=5	Free	y’’=0	y’’’=0

In the following track configuration figures, the thick black line (designated as “Track” in the legend) indicates the physical track shape and is associated with the left y-axis, Track Elevation (m). The zero elevation on this axis refers to the top deck surface. The dashed red line indicates the instantaneous centripetal acceleration experienced at track position x (m) and is associated with the right y-axis, Centripetal Acceleration (g). Each figure includes a solid black circle on the “Track” line to indicate the position where the glider achieves the launch velocity of 500 kts.

Alternative Track Configuration 1

During subsequent mathematical analysis, the track shape was controlled mostly through specifying the track starting elevation. For the first alternate track configuration considered, Figure 22 – Case 1: Track Shape and Centripetal Acceleration, the curved section was shifted to early in the track with the only constraints at x=0 being y=0 and slope=45º down. The top to bottom track height was approximately 27 meters with a resulting maximum centripetal acceleration of approximately 88g.

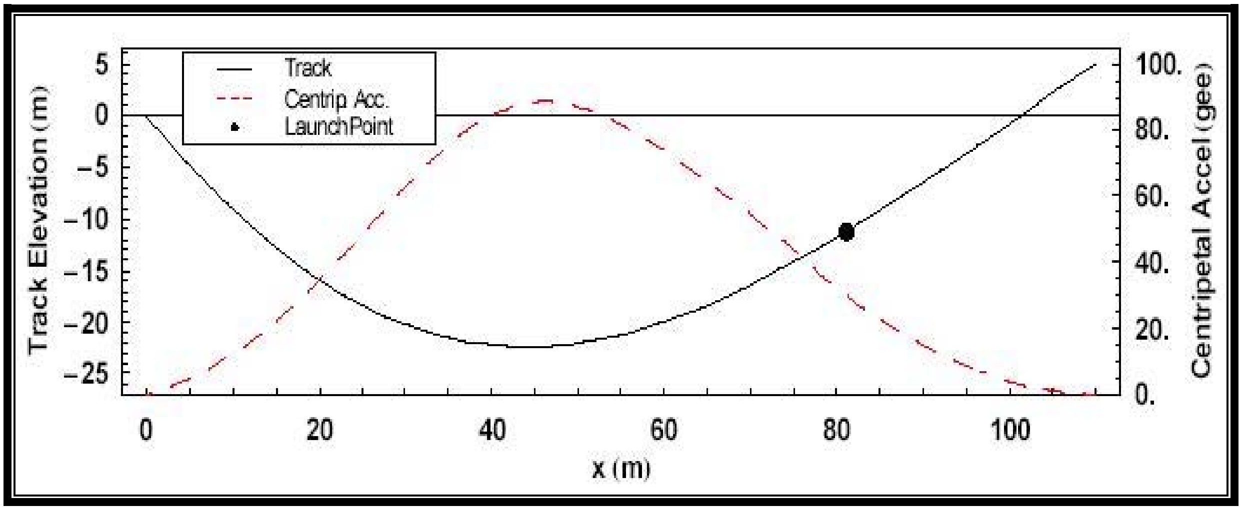


Figure 22 – Case 1: Track Shape and Centripetal Acceleration

Alternative Track Configuration 2

For the second track considered, Figure 23 – Case 2, the slope, curvature and jerk requirements are applied at x=0, and the starting elevation is not fixed. This results in a maximum centripetal load of approximately 42g. The top to bottom track height is approximately 32 meters.

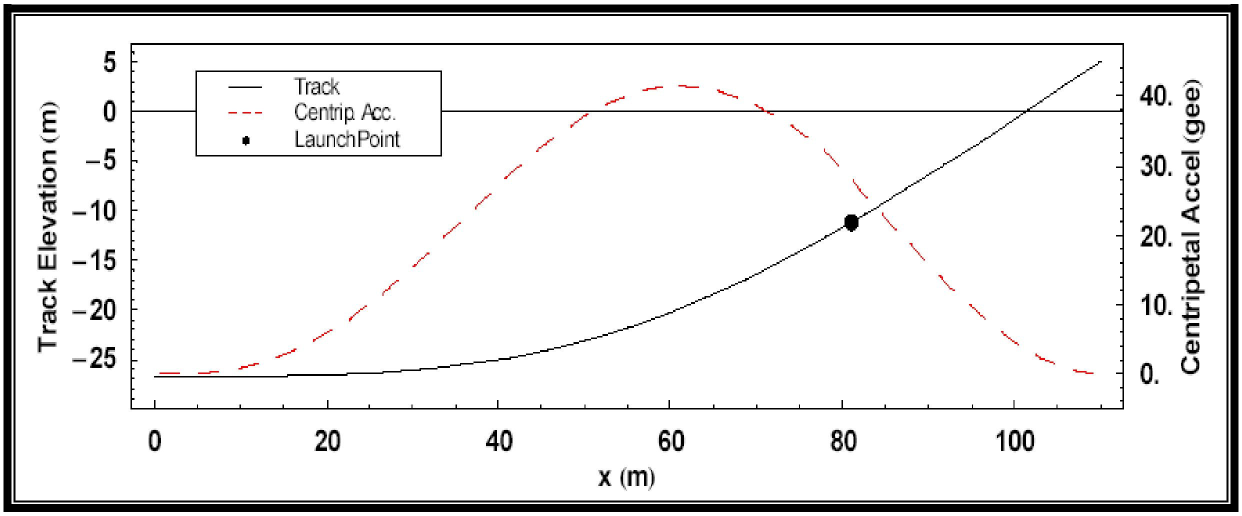


Figure 23 – Case 2: Track Shape and Centripetal Acceleration

Alternative Track Configuration 3

In the third track configuration considered, the slope, curvature and jerk requirements were applied at x=0, and the starting elevation was fixed at y=-20 meters. For this case, depicted in Figure 24 – Case 3, the maximum, centripetal load is approximately 62g and the top to bottom track height is 25 meters.

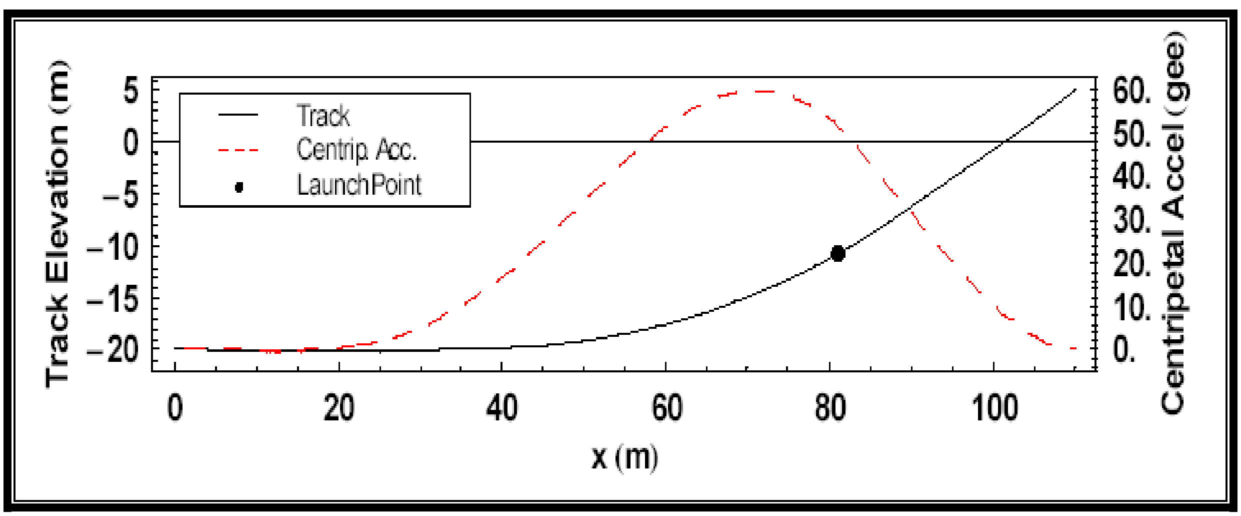


Figure 24 – Case 3: Track Shape and Centripetal Acceleration

Alternative Track Configuration 4

For the fourth track considered, the slope, curvature and jerk requirements are applied at x=0, and the starting elevation is raised to try to fit the 50 ft requirement. Referring to Figure 25 – Case 4, one can see the maximum centripetal load is approximately 110g. In addition, the track is shown to have an inflection point; a reverse centripetal acceleration of approximately 13 gee. The top to bottom track height in this case is approximately 17 meters.

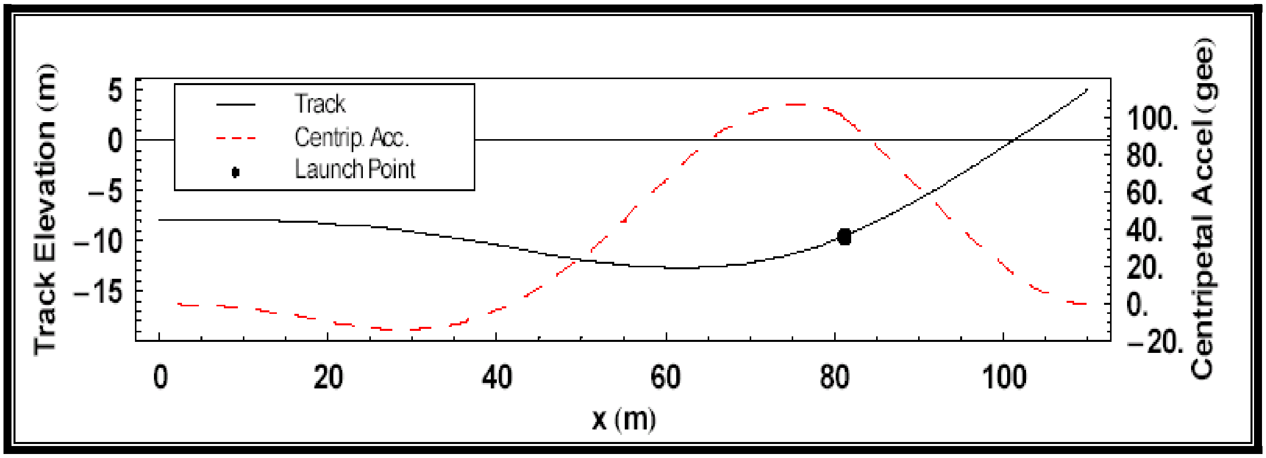


Figure 25 – Case 4: Track Shape and Centripetal Acceleration

Alternative Track Configuration 5

The fifth track configuration considered retains the slope, curvature and jerk requirements at the start of the track, and the curvature and jerk requirements at the end of the track, but leaves the starting elevation free to move and relaxes the launch angle to 20º. As shown in Figure 26 – Case 5, the maximum centripetal acceleration is approximately 30g with a top to bottom track height of approximately 20 meters.

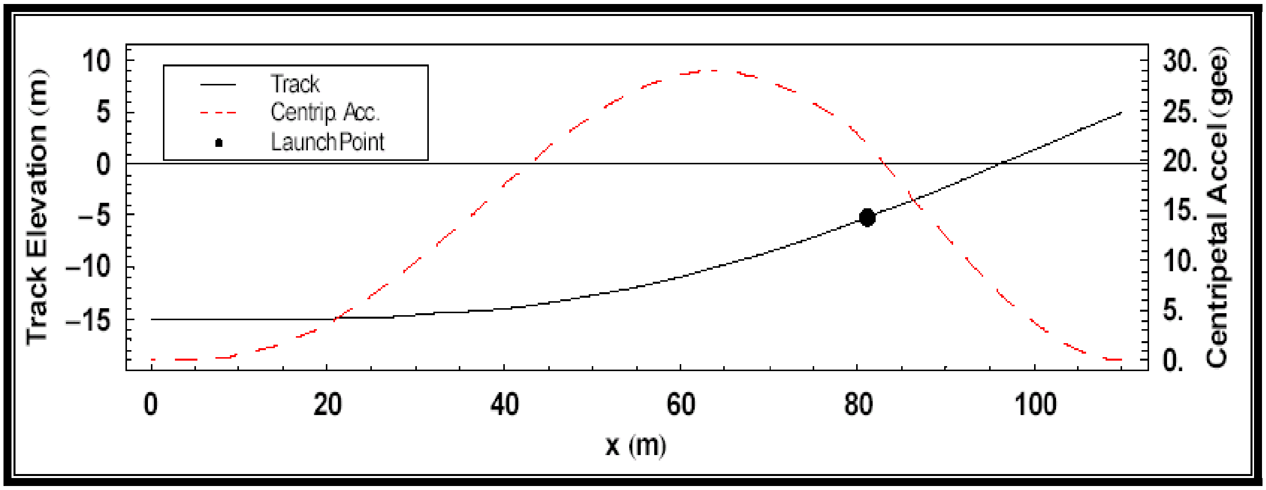


Figure 26 – Case 5: Track Shape and Centripetal Acceleration

Alternative Track Configuration 6

For the sixth track configuration, the slope, curvature and jerk constraints are imposed at the start of the track, with the starting elevation fixed at 11 meters below the deck. At the end of the track, the curvature and jerk requirements are maintained while the launch slope is reduced to 20º. As can be seen in Figure 27 – Case 6, the maximum centripetal acceleration is now approximately 40g, while the top to bottom track height is 16 meters.

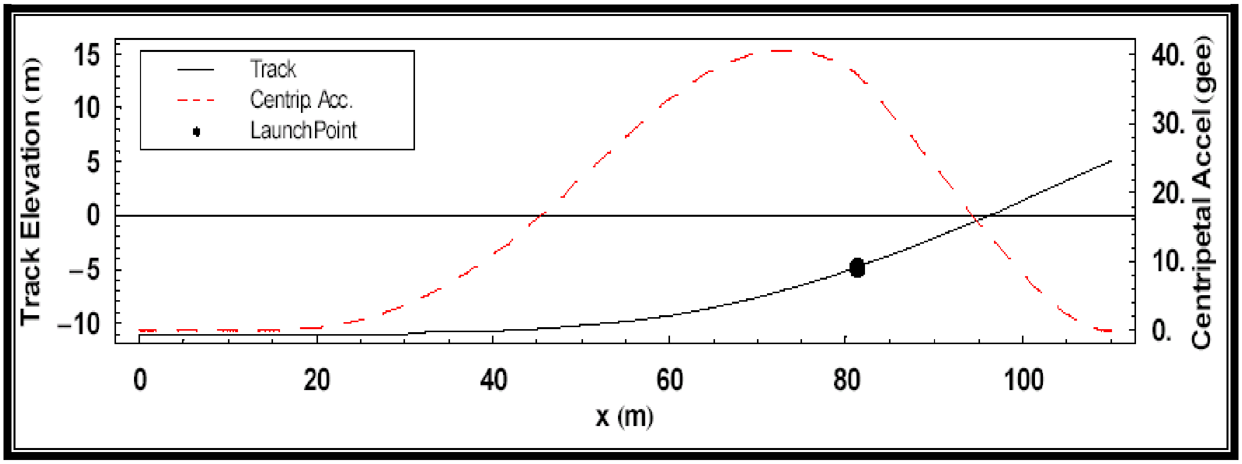


Figure 27 – Case 6: Track Shape and Centripetal Acceleration

Alternative Track Configuration 7

For the final track configuration investigated, the slope, curvature and jerk requirements are met at the track starting location, with the starting elevation fixed at 11 m below deck. At the end of the track, the curvature and jerk requirements are retained, but the slope is left unfixed. In this case, Figure 28 - Case 7 shows that the maximum centripetal acceleration is about 25g, with a top to bottom span of 16 meters. The slope at the end of the track for this case is calculated to be about 16º, roughly half of the optimum angle.

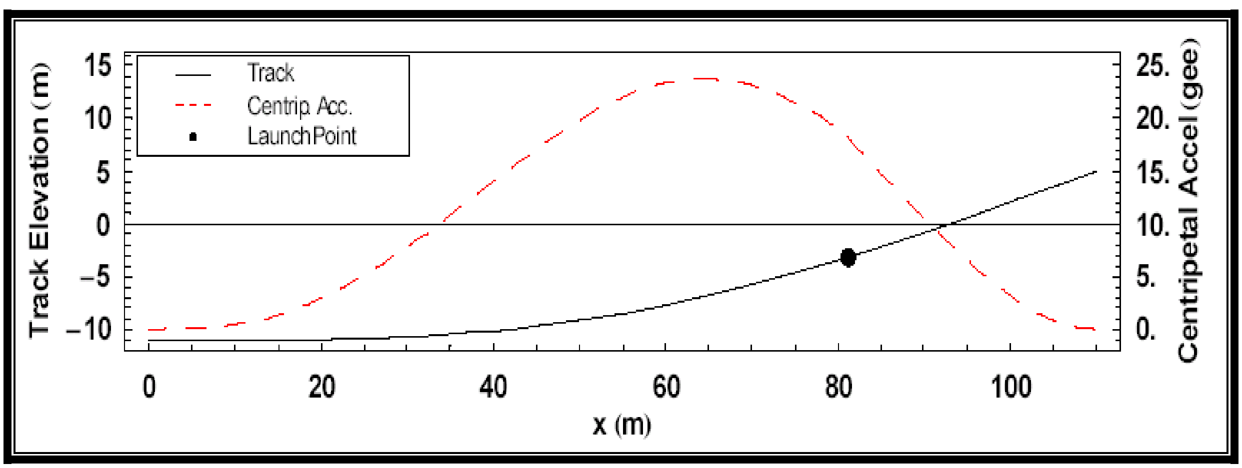


Figure 28 – Case 7: Track Shape and Centripetal Acceleration

Track Variations and Resultant System Effects

In conclusion, all seven designs have smoothly varying curvature and zero angular momentum at launch. An attempt to reduce centripetal loading by simply moving the curve to the front of the track was counter productive. Results indicate the top-to-bottom track height has the most significant effect on centripetal loading. It is noted that requiring a 30º slope at the end, with curvature and jerk requirements establishes a "natural" track height. Shortening the track length may also reduce the centripetal loads.

Table 13 summarizes the centripetal loading and track span for all seven cases.

Table 13 – Summary of Case Results

	Maximum Centripetal Acceleration	Top to Bottom Span	Notes
Case 1	82g	27 meters	
Case 2	42g	32 meters	
Case 3	60g	25 meters	Recommended for 30º angle
Case 4	110g	17 meters	Inflection point in track
Case 5	25g	20 meters	Recommended for 20º angle
Case 6	40g	16 meters	
Case 7	25g	16 meters	16º launch angle

After review of the test cases, Case 3 is recommended if the 30º launch angle is considered critical, while Case 5 is recommended if the launch angle may be relaxed to 20º. Case 3 offers the lowest centripetal load for the shortest top-bottom span at the 30º launch angle. Case 5 offers the absolute lowest centripetal loading, while requiring a top to bottom track height that is still less than what is required for Case 5.

Structural and Thermal S&T Gaps

There are many concerns with using a rail gun as the actuator in the ALDS Launcher System including the material science and machine dynamics of the aircraft and track interface. The use of a curved versus straight track has fundamentally not been addressed, and conductor interface/wear continues to be an issue with DARPA and US Army EM gun development efforts. Additional research efforts are necessary to address thermal load management across power electronics, storage, superC, etc.

Structural and Thermal Summary

A kinetic launch concept and track configuration that drives critical requirements (structural and power) has been presented. Technologies exist for both near term and far term solutions with varying maturity and risk. Selected S&T / demonstration projects and ongoing efforts could yield a prototype ~ 2020.

Conclusions

A trade study and technical assessment identified and evaluated the most suitable candidate machinery solutions for a Linear Electric Launch Actuator System capable of supporting the preliminary Advanced Logistics Delivery System (ALDS) launch system requirements. System requirements for four technology areas, (a) launch actuator, (b) power electronics, (c) energy storage, and (d) track configuration were identified, and candidate technologies for the major sub-systems were selected. Two options were identified for the overall linear actuator configuration.

The technology development necessary to bring these concepts to final design, prototype demonstration, and operational fruition are provided in the following Technology Development Summary.

Technology Development Summary

Attempts to develop an ALDS Launcher System that meets ALDS requirements in the 2015 timeframe using the solutions proposed would be marginal unless specific technology development efforts are addressed in the near-term. The defined topic areas are launch actuator, power electronics, energy storage, track configuration and structural integrity, and thermal management. The areas of concern within each heading are discussed below.

Launch Actuators

LBSCMM (Linear Bulk Superconductive Magnetic Motor)

The low temperature (40°K) LBSCMM was chosen as the design of choice for the ALDS application because it provides the highest force vs. rotor weight required, allows much higher magnetic generation than the linear induction or linear permanent magnet motors, and has a nearly unity power factor capability. Continued research in the extremely *high field* superconducting magnet technologies with *extremely low temperatures* should make this technology viable in the near-term.

High temperature magnetic material engineering and design capabilities should be stressed in the long run, in particular, higher temperature super-conducting magnets having high field strength characteristics that exceed 20 Tesla. In addition to this, superconducting material research to reduce AC Losses, and wire development for high field magnets for large bore sizes, greater than 0.5 m, needs consideration.

High field, large bore superconducting magnets are an ongoing, research topic at NRL, ORNL, LANL, BNL, DOD, and various universities. In the area of reduced AC losses in superconductors, the DARPA SuperHype program with NRL, American Superconductor, ORNL, and NSWCCD are actively performing research. High field magnets with bore sizes greater than 0.5 m are long-term objectives at NHMFL, MIT Magnet Lab, and the LANL.

Deployment of an ALDS system will require investment in technology development of high power- high gee capable cryo-coolers and related cooling components.

Rail gun

Rail gun barrel, manufacturability and bore life issues must be addressed. Rail gun barrels, unlike conventional gun tubes, are multi-piece structures that must be assembled and operated without compromising bore straightness or dimension [10]. Damage to the bore materials (rails and sidewall insulators) of the gun must also be avoided, and more fundamental research is needed to develop a long bore life gun tube and examine the impact of using a curved track. Finally, the most significant challenges, facing the compulsator pulsed power supply, are the switching systems required and the thermal management of the high-speed rotor. Near term switching systems employing vacuum arc switches will likely be adequate for naval applications, although the emergence of Silicon Carbide (SiC) solid-state devices may provide a more compact switch with reduced losses in the future [8].

Energy Storage Technology

Current energy storage technologies are adequate to meet the ALDS Launcher System requirements. Future development efforts should address general improvements in power densities, i.e. energy storage weight and volume reductions.

Power Electronics

The most critical power electronic needs for the ALDS Launcher System are high power switches and high frequency switching algorithms. Current requirements cannot be met by Commercial-off-the-shelf (COTS) equipment. This application requires a militarized solution.

Track Configuration and Structural Integrity

In the near term, efforts should focus on of the development of a high rigidity curved track capable of handling high g forces. In addition, efforts in track material science are necessary to address rail insulator ablation during operation.

Thermal Management

No issues identified.

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